Programme Area: Energy Storage and Distribution

Project: Heat Storage

Title: Feasibility of Geological Heat Storage Final Report

Abstract:

The Final Report was produced by Buro Happold, the Lead Co-ordinator for the Feasibility Study of Geological Heat Storage in the UK project and
The project was characterised as a good study that has provided a better understanding of the potential for heat storage in the UK and provides an insight for the
potential next steps should a pilot study be contemplated.

Context:

Heat is the biggest end use of energy in the UK - most of it is used for heating homes and providing hot water. This research project examined the feasibility of capturing large quantities of waste heat from power stations and industrial processes and then storing it underground for later use in homes and offices. It investigated the cost effectiveness and practicalities of storing large quantities of heat for long periods of time to meet a significant proportion of the UK's winter heat demand. It evaluated the practical limits for this type of storage, the technology development needs and where in the country large-scale heat storage could be most effectively exploited. International consulting engineers Buro Happold completed the research project in 2011.

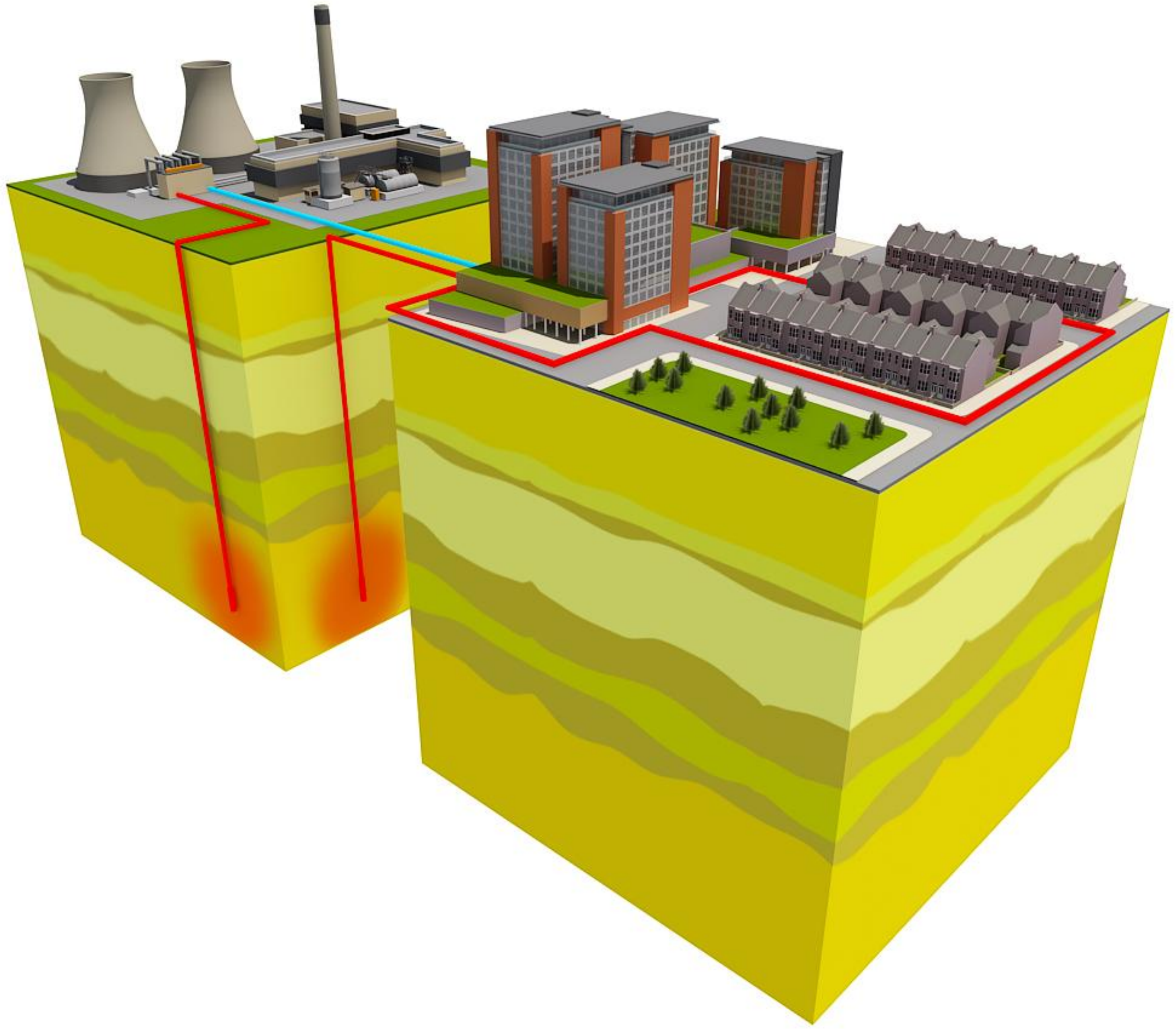
Feasibility of Geological Heat Storage in the UK

Buro Happold

EGEC

IFTECH

UNIVERSITY OF CAMBRIDGE



Final Report

Revision	Description	Issued by	Date	Checked
00	Draft	JSD	14/06/2011	HM
01	Additional Numerical Modelling Details in Chapters 5 and 8	JSD	15/06/2011	HM
02	Review and addition to address comments from ETI panel members	JSD	19/08/2011	HM/ AY
03	Update Executive Summary	JSD	30/09/2011	AY

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author	James Dickinson
date	19/08/2011
approved	Hugh Mallett
date	19/08/2011

Team

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James Dickinson

Project Collaborators

IF Tech Ltd
Cambridge University Technical Services
British Geological Survey (Data)
European Geothermal Energy Council

Executive Summary (Short Version)

Study findings

This feasibility study assesses the potential for large scale geological heat storage (sometimes termed heat capture and storage) in the UK and has been commissioned by the Energy Technologies Institute (ETI). The results of the study suggest that large scale geological heat storage is technically feasible, and depending on future energy prices can be economically viable. The main benefits of such storage lie in the potential to help improve thermal efficiency of existing and future power stations (currently around 35-55%) by enabling the practical and viable use of their waste heat output. This could increase the overall system efficiency to approximately 80%. By decoupling electricity and heat generation it can provide flexibility to deal with variations in supply and seasonal demand. In the longer term it can provide low or zero carbon heat when climate change targets mean using natural gas is not longer acceptable. Additional benefits include reducing demand on the electricity system by reducing the amount of heat demand switched from natural gas to electrically driven heat pumps.

Under ideal conditions the unit cost of heat delivered in bulk to a city centre has been shown to be less than £100/MWh, and in some cases as low as £20/MWh where the transmission pipe work to high demand areas is relatively short. Without storage the equivalent direct heat unit cost range is only reduced by 2-12% as the dominating cost is the district heating transmission pipework and peripheral plant. The indicative capital cost (including the heat storage system, primary district heating pipework, backup heating plant, pumps etc.) is between £0.99million/MW for a 10km district heating main, and £2.25million/MW for 100km. This is based on a nominal average daily peak load of 250MW and extracting heat from a power station at 120°C. It does not include the heat take off plant at the power station, district heating distribution and building connections within the respective town or city. Ideal conditions are where:

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Under ideal conditions the unit cost of heat delivered in bulk to a city centre has been shown to be less than £100/MWh, and in some cases around £50/MWh. The indicative capital cost (including the heat storage system, primary district heating pipework, backup heating plant, pumps etc.) is between £0.99million/MW for a 10km district heating main, and £2.25million/MW for 100km. This is based on a nominal average daily peak load of 250MW and extracting heat from a power station at 120°C. It does not include the heat take off plant at the power station, district heating distribution and building connections within the respective town or city. Ideal conditions are where:

1. The available annual heat off-take from the power station and the heat demand are balanced on an annual basis (i.e. the available heat supply does not outstrip the demand at all points in time, in which case direct heat provision without storage would be economically and practically preferable and vice versa).
2. The power station from which the heat energy is taken off is not far from the demand centres (<25-50km). Beyond this distance the capital cost of the heat network represents more than 50% of the total capital cost. Extensive existing heat networks must be present in order to make use of the large quantities of heat available and to provide an acceptable unit cost of heat. Where heat networks are not present a policy framework is required to drive the further development and take up of district heating in suitably high density areas.
3. The area is underlain by conditions suitable for geological storage, namely rapidly water/heat transmitting aquifers located >200-300m below ground level (bgl). Aquifers at this depth allow higher storage temperatures (120°C) due to their separation from potable water aquifers and ability to contain relatively high pressures.

Scoping of next steps

A pilot study should be undertaken following the selection of a suitable site chosen on the basis of criteria outlined in this report. The ultimate selection of a suitable pilot study, for a suggested 25MW aquifer thermal energy storage (ATES) system should go hand in hand with consideration of the following:

1. Stakeholder consultation with ETI members, power companies, local authorities and government departments (DECC and DEFRA)
2. The practicability and detailed analysis of heat quantities that can be taken off in association with power station operators.

3. An environmental impact assessment (EIA) and risk assessment in consultation with the Environment Agency and the respective local authority as a test case and on the basis and for an actual site.
4. Treatment and mitigation options, post site specific water chemistry and geotechnical testing.
5. "Industrial Capacity" testing by means of main contractor (equipment manufacturer) consultation.
6. Selected sites should be as close as possible to an existing district heating system in the UK, possibilities include:
    - Borehole Storage: Southampton, Sheffield, Nottingham, Leicester
    - Aquifer Storage: Birmingham, Southampton, Manchester,

A phased pilot scheme is suggested with the following indicative costs:

Borehole Pilot Study (not including 1-6 above)

- Phase 1 and 2 (Single borehole development) - £100-150k depending on geological conditions and depth
- Phase 3 (Borehole Array Development) - £400-600k depending on above and array size

Aquifer Pilot Study

- Phase 1 and 2 (Single well development) - £1.5-2m depending on hydrogeological conditions and depth
- Phase 3 (Wellfield Array Development) - £5-7.5m depending on the above and array size

Executive Summary (Extended Text)

National strategic and environmental benefits

The key benefit of large scale geological heat storage in the UK is the potential reduction in the dependence on natural gas for space heating by aiding the practical feasibility of using waste heat from existing and future power stations for district heating. In the short to medium term this provides improvements in security of energy supply and reductions in carbon emissions. The UK's climate change targets (80% reduction in greenhouse gas emissions) mean that by 2050 the carbon intensity of heating will need to be close to zero. Therefore, in the longer term, using heat storage in conjunction with waste heat transmission and distribution from nuclear or carbon capture has the potential to provide a low or zero carbon source of energy for space heating when coal, oil and natural gas can no longer be used. It could also reduce dependency on renewable electricity sources linked to heat pumps for heat which will require significant increases in the capacity of the electrical transmission and distribution system.

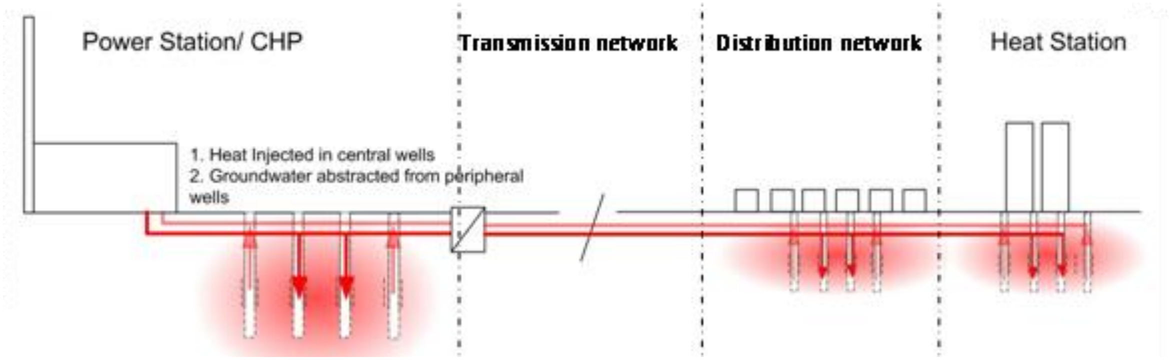
Context and background

In the UK overall fuel efficiency of electrical generation is limited by the centralised positioning of power stations in relatively isolated locations and the current inability to use low grade heat. Displacing the use of high grade fuels, particularly natural gas which is currently widely used, and in future electricity, for space heating by using the low grade heat output from power stations can significantly increase the fuel efficiency of power stations. Large scale geological heat storage offers the opportunity to make use of this low grade heat whilst providing some of the flexibility and ability to meet peak loads inherent in the natural gas system linked to seasonal heat demand.

An important aspect in the context of this study is the electrical and heat demand profiles throughout the year. Currently electricity demand is relatively constant throughout the year whilst heat demand is seasonally led due to dominant space heating requirements during colder periods. Peak space heating demand is estimated to be at least 120,000MW with a seasonal variation of a factor of greater than 5. Introducing a storage mechanism to seasonally store heat from power stations provides the potential to balance this seasonal mismatch whilst avoiding excessive investment in peak load plant which is only used on a few days per year.

The possibility of using heat from power stations has been considered previously but this report develops a more detailed assessment of the technical and economic feasibility. This report differentiates from previous waste power station heat projects due to its consideration of:

1. The utilisation of large scale geological heat storage to address seasonal imbalances in supply and demand for heat
2. The "quality" of heat - its temperature and the marginal reduction in the electrical efficiency of power stations in order to generate useful heat output
3. The heat network design from power stations to local distribution (see diagram below)



Schematic of Heat Network System

4. The density of heat demand required to make heat networks economically viable.

Results of the research include:

1. There are numerous examples of heat storage in Europe and Northern America although these systems are generally at a relatively low temperature and at a smaller *building* or *community* scale. Examples of storage systems operating at temperatures >50°C are limited.

2. The preferred storage media are deep (200m-300m bgl) aquifers. The is because these deep aquifers are mostly brackish in nature and not as sensitive or regulated as shallow freshwater aquifers utilised for potable water supply.

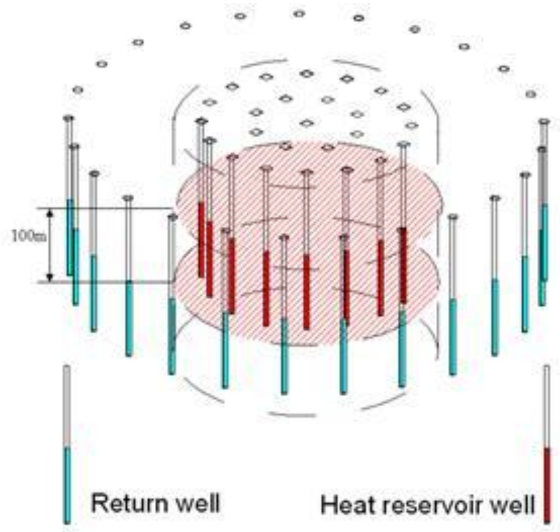
3. Ground stores are likely to operate with a heat storage efficiency of 60-85%, depending on the storage temperature and hydrogeological conditions. A period of 4-6 years is required to reach steady state conditions in the large aquifer stores which were modelled. During these initial years losses can be higher.

4. The main considerations for designing ground stores include: accurate injection/abstraction profiling, geological and hydrogeological analysis, determining suitable water treatment, assessing efficiency and groundwater flow, and determining a regulatory regime.

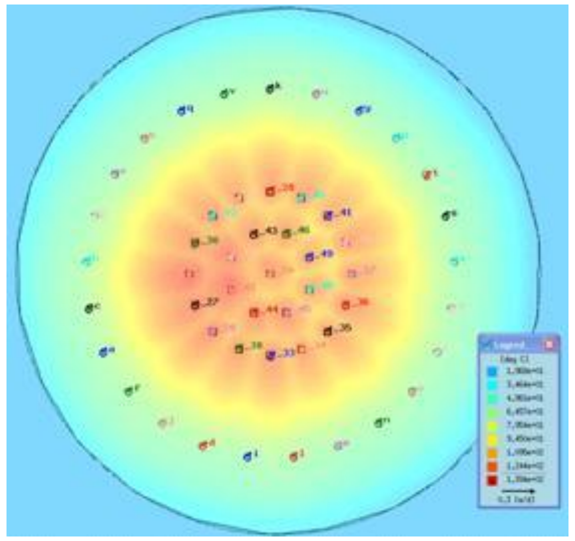
5. The most important operational aspects are: water treatment, monitoring, heat injection, consumer heat use (which must match design assumptions), maximising efficiency and ensuring ongoing regulatory compliance.

6. Analytical and numerical modelling techniques to support the design and operation of below ground storage systems are well developed. Based on the modelling completed a heat storage design should be based on the optimum combination of a number of key parameters, including: the aquifer thickness, aquifer permeability and temperature differentials.

7. Closed loop borehole thermal energy stores (BTES) systems can be deployed in all regions of the UK. Open loop aquifer thermal energy stores(ATES) is limited to areas with suitable hydrogeological conditions, but data on deeper strata most suitable for these systems is limited. ATES systems are estimated to be feasible in 20-40% of the UK, but further ground investigation data is required to determine this more accurately.

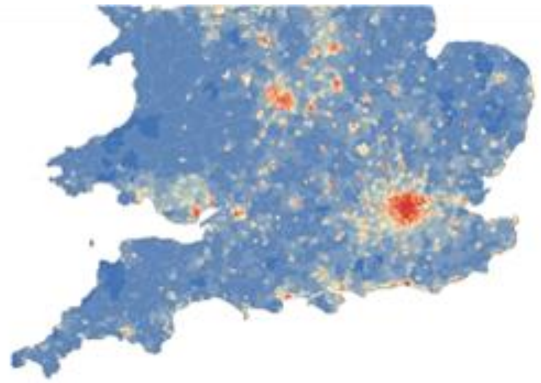


Baseline Aquifer Thermal Energy Storage (ATES) System



Plan View Thermal Modelling

8. The economic viability of district heating is a limiting factor to the applicability of large scale heat storage. Only a certain proportion of the UK has a sufficiently dense demand for heat to make heat networks viable. Spatial gas use data from DECC was used to formulate heat density maps for Great Britain with further supporting information for Northern Ireland. Using typical economic thresholds for district heating around 10% of the current UK gas fired heat demand is deemed economically viable, consistent with previous studies commissioned by DECC. A further 44% deemed potentially viable in the future should energy prices increase, but this would require the extension of heat networks to low density suburban areas where other technologies may provide lower cost heat.



Heat Density Map for the UK

Agglomerated Heat Density using current and future economically viable thresholds

9. At present the regulating authorities in the UK are likely to object to the storage of higher temperature heat in near surface aquifers that are currently used for drinking water, or other uses where there are existing licence holders. There is no clear benefit from using high temperature heat (200°C) outputs from power stations for a district heating network. Medium temperature heat (120°C) is sufficient for the required flow temperatures (80 – 85°C) after losses from the heat store and heat network. Furthermore, cost, technical problems and high electrical power production losses are associated with high temperature systems. There are significant costs associated with low temperature (35°C) systems (i.e. requirements for larger diameter pipework and heat pumps) which do not apply to medium heat systems. Medium temperature systems are recommended due to their lower costs, the existence of well proven heat network systems and the technical feasibility of storing heat below ground at this temperature. However, it should be noted that the geo-chemistry associated with this option is extremely location specific and must be well understood to avoid potential problems from precipitation of minerals.

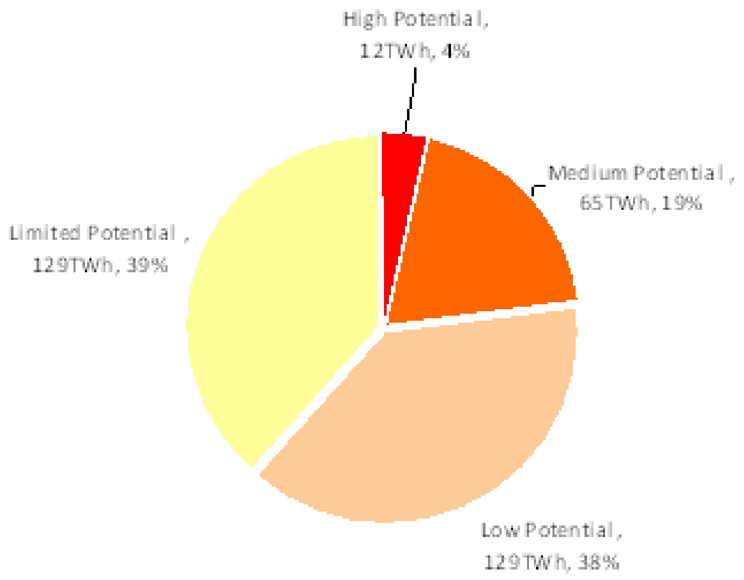
10. Direct heat provision without ground storage is around 10-50% cheaper in capital cost terms than a ground storage system, depending on distance to the heat load. Systems without storage are therefore preferred to storing heat in the ground prior to delivery, due to reduced efficiency, and higher capital and operational costs of the latter. For this reason some locations have no justification for storage although the geological or hydrogeological storage

potential is high. In these locations, potential heat supply is much higher than local demand throughout the year so there is no benefit from seasonal storage. Similarly where heat supply is much lower than demand throughout the year some additional form of heat provision is needed either through conventional means (e.g. boilers or heat pumps) or through the strategic development of additional power stations in the area. This dynamic between local heat supply and demand will be a leading factor in decision making for the siting of new heat and power generation.

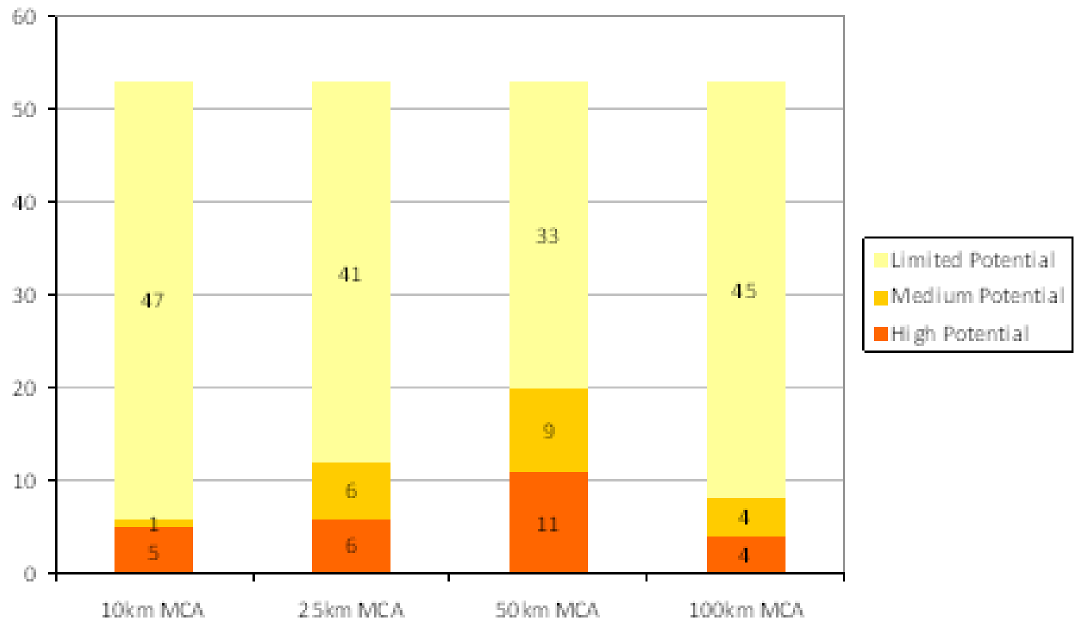
11. A pilot study is required to fully assess the design and operational characteristics for this scale and use of system. Each installation will require an extensive site investigation to develop and prove the potential at each location.

12. The multi-criteria analysis (MCA) methodology adopted for the analysis considered the geological potential, nearby heat demand and proximity to a power station. The number of areas in the UK showing either high or medium potential equated to 10% of the UK total heat demand.

13. A further MCA was undertaken to assess the availability of preferred geological storage and proximity to power stations located close to areas of high heat demand. At a distance of 25km 12 of the UK's 52 large power stations (>500MW) show high or medium potential for geological heat storage. Increasing the primary heat network length to 50km increases this to 20 large power stations.



Multi-Criteria analysis for MSOAs



Power Station MCA Results

Contents

Glossary

ATES	Aquifer Thermal Energy Storage
AW	Abstraction Well
BTES	Borehole Thermal Energy System
BGS	British Geological Survey
CHP	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance
EA	Environment Agency
ELT	Entry Load Temperature
EST	Entry Source Temperature
EWT	Entry Water Temperature
GLHE	Ground Loop Heat Exchanger
GSHP	Ground Source Heat Pump
GWHP	Ground Water Heat Pump
HP	Heat Pump
IEA	International Energy Agency
LLT	Load Leaving Temperature
NIEA	Northern Ireland Environment Agency
PE	Polyethylene (HD – High Density, MD – Medium Density)
PETS	Primary Energy Transfer Station
SETS	Secondary Energy Transfer Station
SEPA	Scottish Environmental Protection Agency
SPF	Seasonal Performance Factor
VDI	Institution of German Engineers

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1 Introduction

The desired outcomes of this research project are to provide:

1. An assessment of the potential economics and contribution of large scale geological heat storage as part of a future UK energy system with significant heat distribution to domestic housing and commercial buildings;
2. Identification of the most promising approaches and their development requirements; and
3. Identification of potential locations and scope for the next stage of technology development and demonstration.

The project has been completed against a backdrop of increasing fossil fuel prices, future energy security concerns and UK carbon reduction targets.

This feasibility report analyses the technical, economic and regulatory aspects of the potential in the UK and concludes with a framework for two pilot studies and a generic delivery plan for the approach.

The project team that completed the report consisted of:

Buro Happold

Project Coordination and Lead – Dr James Dickinson

All analysis and review not noted below

IFTech

1. Literature Review Input
2. Numerical Modelling of Homogeneous Aquifers
3. Input into Capital Costing, Schematic Development
4. Strategic review and Expert Panel Member: Aart Snijders

Cambridge University

1. Analytical Modelling – Professor Andrew Woods (BP Institute)
2. Strategic Review and Expert Panel Member: Professor Peter Guthrie

European Geothermal Energy Council

Literature Review Input and Expert Panel Member – Dr Burkhard Sanner

British Geological Survey

Data provision and geological research consultancy

This report supersedes three interim reports completed during the project.

Chapter 2 provides a Literature Review of

1. Operational experiences from different systems installed in Europe and elsewhere
2. Historical research in the field of ground heat storage, including identification of significant parameters, characteristics and fundamental relationships for different approaches

Chapter 3 provides an assessment of Geological Formations for Heat Storage, including:

1. UK Geology Overview
2. Key Parameters for Heat Storage and Development of Initial Conceptual Models
3. UK range in key systems variables

Chapter 4 identifies the key technological requirements and presents a series a potential system configurations

Chapter 5 provides a review of the salient analytical and numerical modelling aspects for both heterogeneous and homogeneous aquifers

Chapter 6 presents the basis for the budget capital costing including the:

1. Ground Storage System including drilling curves, economies of scale for both closed and open loop systems
2. Above ground system including district heating, conventional back up plant and other peripheral items

Chapter 7 provides the development of the economic and carbon modelling for the system including end user demand profiles, and ground heat abstraction and injection.

Chapter 8 provides analysis on 2 potential pilot studies for Fiddler's Ferry and Hartlepool Nuclear Power Stations including:

1. Geological descriptions
2. GIS Interpretation
3. Modelling of Capacity and Energy Distribution Systems
4. Development of modular schematics for the Well field and Low and Medium temperature circuits
5. Capital and Operational Costing including the Cost of Heat

Chapter 9 provides an overview of the GIS Analysis Methodology, Data Layers and presents example GIS sheets

Chapter 10 builds on Chapter 9 by providing a review of the Multi-Criteria Analysis (MCA) that has been completed to assess the potential for geological heat storage

Chapters 11 to 14 provide contextual analysis and review on Geotechnical, Environmental, Regulatory Aspects and the potential for Intellectual property issues.

Chapter 15 provides an assessment of

1. Industry Capacity and Gap Analysis
2. Delivery Process and Options
3. Funding and Procurement
4. Potential Team Organogram

2 Literature Review

2.1 Introduction to Ground Energy Systems

Through researching the field of ground energy systems two distinct resources have materialised. Firstly, there are higher temperature and enthalpy resources that can be tapped into, where the heat is generated from beneath the earth's crust (Dickson and Fanelli, 2003). This is usually typified by a magmatic intrusion that has reached relatively shallow depths. This heat can be used for electrical power generation or for space heating. Secondly, there are those systems that use the ground as a storage medium and make use of moderate temperature swings in the ground, compared to ambient air, thus providing a positive thermodynamic advantage for use in either heating or cooling a building (Bose et al., 2002). The energy in the ground "… is transferred to and from the earth's surface by solar radiation, rainfall, wind etc. Only a small part (less than 3%) of the stored energy in the earth's crust comes from its core" (Rawlings, 1999). This characteristic makes it inherently different to the former ground energy resource where heat is derived from the internal core of the earth. Also, due to the thermal mass of solid geology and groundwater, and huge volume beneath the surface there is an inherent potential to store large quantities of heat.

The majority of the internal energy that was produced was caused by gravitational contraction of the planet as it was formed (Boyle, 2004) but is now in some way maintained by radiogenic heat that is continually generated by the decay of long lived radioactive isotopes of uranium, thorium and potassium. Dickson and Fanelli (2003) reported that the total heat content of the earth is in the order of 12.6 x 10^{24}MJ of which 5.4 x 10^{24}MJ is contained within the earth crust. Obviously this is an immense resource but only a fraction is currently available to mankind. The earth's crust is for example about 20-65km deep in continental areas so it is clear that it is not always going to be economically viable to extract energy from such deeper resources.

In the context of the UK, Batchler et al (2005) have stated that the economic utilisation of naturally occurring higher temperature and enthalpy geothermal remains unachievable due to the depth of suitable resource and comparative cost of fossil fuels. Only one such system is currently in operation in the UK in Southampton. This has been operational since the early 1980s and was heavily funded by the Department of Trade and Industry (DTI).

In addition to naturally occurring ground energy resources, the ground does theoretically provide the potential for large scale heat storage using waste streams from above ground processes. An overview of the main underground thermal energy storage (UTES) systems is shown in Figure 1.

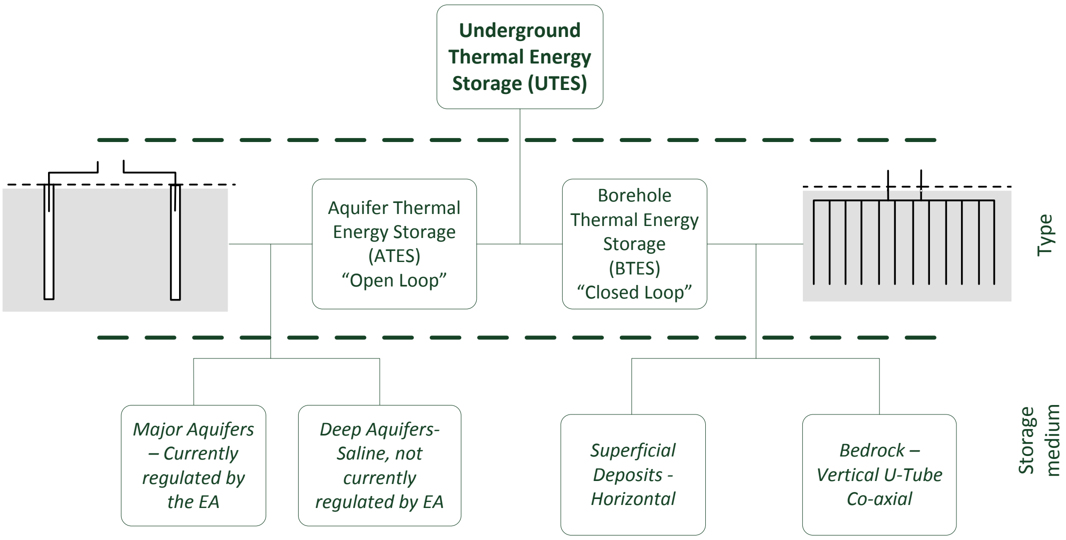

Figure 1 Ground Energy Storage System Overview

The approaches currently deemed appropriate in the UK for more conventional ground source heat pumps (GSHPs), both technically and economically, use energy stored in the near surface geology. The energy balance is maintained by energy from the sun, a small heat flux from beneath the earth's crust and the cyclic loading of the ground during heating and cooling modes.

There are essentially two variations of ground energy systems, those using a *closed* network of pipes or tubes buried beneath the ground, and *open* loop systems that abstract groundwater from aquifers. The use of the following expressions will be used extensively in this study to reflect the use of both variations for heat storage.

- Borehole Thermal Energy Storage (BTES)
- Aquifer Thermal Energy Storage (ATES)

The further prefixes of LT[1] (low temperature), MT[2] (medium temperature) and HT[3] (high temperature) are also used extensively.

In the past, the majority of theoretical development has focussed on vertical and horizontal closed loop systems, using bespoke boreholes and trenches, and open loop systems; abstracting and discharging water from an aquifer beneath the

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[1] LT = Low Temperature = ~35°C

[2] MT = Low Temperature = ~120°C

[3] HT = Low Temperature = ~200°C

development. It is for this reason that other marginal low temperature approaches are essentially overlooked in preference for those options that are “ready to go”. This necessary step reduces uncertainty in the applied design methodology used in the study and hence enables the research themes to be approached more confidently and in more depth.

It is generally important in the success of a ground source system to establish a thermodynamic advantage from using the ground. This usually means the application in temperate climates with significant seasonal swings. However, in the context of this study the use of the ground is to simply store heat so whilst the boundary conditions may affect the relative efficiency and viability of the system the undisturbed ground temperature is not a lead acceptance criteria.

Using the ground as a method to store and exchange heat is not a new technique although the relative uptake of high temperature systems has been much lower than for low temperature systems. In the context of this study lower temperature systems can be denoted as those systems operating in the region of -5 to ~30°C. This range is usually the result of evaporator and condenser temperatures from heat pumps or in “free cooling” mode, direct from cooling distribution systems in buildings. The resulting geochemistry, geotechnical and engineering challenges are relatively well understood and easy to overcome for such systems. In addition the regulatory controls enforced by the Environment Agency generally allow for low temperature systems to be installed in the majority of instances[4].

For higher temperatures systems, operating at temperatures greater than 30°C, there have only been a small number of either experimental, demonstration or commercial installations. The higher the storage temperature is above ambient temperature, the more appropriate it is to use directly for heating purposes. With low temperature heat, advanced heating distribution with very low supply temperatures (<30°C) are generally required, or the temperature has to be increased further by use of a heat pump or other heating plant. With sufficiently high supply temperatures from the store, standard heating systems can be fed directly, or heat pumps, if still necessary, will demonstrate high efficiencies.

A clear advantage of closed systems is the independence from aquifers and water chemistry, whilst the main advantage of open loop systems is the generally higher heat transfer capacity of a well compared to a borehole. This usually makes the application of ATES the lowest cost alternative. This of course, is if the subsurface is hydro-geologically and hydro-chemically suited.

2.2 History of UTES Systems

A useful description of the history of high temperature UTES systems is provided by Sanner (1999). This section provides a summary of this publication in the context of the study.

The use of HT-UTES was first published by Margen (1959). However, its purpose was not strictly heat storage, but electric power storage. In this example hot water would be stored in very deep caverns under pressure, to be later used for generating steam and electricity. The intended heat source was nuclear power generators, a new relatively new technology at this time. Later on, the idea was again reviewed in 1971 in Sweden and in 1973 in France, but no HT-UTES installations were constructed (Hadorn, 1988).

Lower temperature UTES (for heating and/or cooling) has a tradition of some 30 years, beginning with aquifer cold storage in China (Sun, 1986). Outside China, the idea of UTES was first published by Brun (1964), who also presented the idea of higher temperature UTES. His idea involved the installation of steel tubes (175 mm ID) in boreholes in rock, in a circular pattern and in series. Loading of the store would be done by steam at 500-1000 °C. The shape and size of the whole store was given as a cylinder with 200 m in diameter and 30 m depth. This system was a closed loop system with initial loading through the central boreholes.

More theoretical work was furthered in the early 1970's (Kazmann, 1971; Rabbimov, 1971), in this case considering cyclic ATES in detail for the first known time. Kazmann described various uses of aquifers and stated with relation to heat pumps: "This would utilize the aquifer for the storage of heat on a cyclic basis and would improve the thermodynamic efficiency of the process by the salvage of waste heat". Meyer and Todd (1973a, 1973b), working for General Electric, then proposed aquifers as a solution to waste heat problems of electric power generation, and suggested the injection of heat up to 340 °F (171 °C). They wrote: "Heat storage wells may be the key to using the high-quality heat produced as electricity is generated; the seasonal heat loads can, through heat storage, be matched to electrical demand" (Meyer and Todd, 1973a:42). This article was translated into German for a journal for the lignite-based power industry (Meyer and Todd, 1974). However, it then took almost 20 years to further a physical installation. This example was installed as part of the Utrecht University's ATES system where waste heat from CHP plants was actively stored in the ground (Van Loon and Paul, 1991).

In Europe, the theoretical consideration of UTES began at about the same time, published e.g. by Gringarten and Sauty (1975), Kley and Nieskens (1975), Delisle (1977), and Werner and Kley (1977). A short experiment with injection of warm water into an aquifer took place in 1974 in Switzerland, with water from Lake Neuchâtel (Matthey, 1977). Hadorn (1988) reports working groups on ATES in Switzerland (in Neuchâtel and Lausanne) and in France (École de Mines de Paris). From the side of nuclear power generation waste heat, Despois and Nougarède (Despois, 1977) proposed a deep aquifer for hot water storage between 100 °C and 200 °C (as later tested in Le Plaisir, (Pfiffer, 1991).

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[4] The Environment Agency in England and Wales only currently directly regulate open loop systems via the requirement for the application for an abstraction licence and discharge consent. Closed loop systems are not directly regulated although the EA do have the opportunity to comment on schemes during the planning process for new building schemes. The Scottish and Northern Ireland equivalents of the EA generally follow regulatory procedures detailed by the EA.

However, the first long-term field experiment with high temperature was conducted in the USA, at Auburn University, Alabam (Molz, 1979). This experiment also offered the first opportunity for validation of numerical models of heat transport in aquifers, and the relevant group with C.F. Tsang in Berkeley became a centre for modelling of ATES. A similar, later well known group on thermal analysis of ground heat formed around J. Claesson in Lund, Sweden, ca. 1980. A first book on ATES was then published in 1980 in the USA (Schaetzle et al., 1980).

In the 1980's, the interest in UTES increased rapidly, and several pilot- and demonstration plants where built, in combination with solar thermal energy (Dalenback, 1990), with waste heat (e.g. "SPEOS", Lausanne; (Saugy, 1985)) or with heat pumps. On seasonal thermal energy storage, a comprehensive guide was first published in 1988 and later translated to other languages (Hadorn, 1988). In the second half of the 1980's storage of cold for space cooling became an issue, and since 1990 cold storage is used in an increasing number of plants in Canada, the Netherlands, Sweden and other countries. A concise report on the state-of-the-art of UTES was produced within IEA ECES Annex 8 (Bakema, 1995).

2.3 Experiences from Experiments, Pilot and Demonstration Plants

It is not easy to generalize experiences from plants of very different nature, and the statistic significance of the results of course is not given for a total of 22 projects reviewed. The projects were classified as:

Experiments: Plants just to carry out experiments, usually no heat delivered to any user, sometimes no storage cycles at all, operated only for a given project period

Demonstration: Plants with the objective to deliver heat to users, but also with certain extend of experimental work and monitoring; a commercial operation of the plants for an indefinite time period was intended (some plants have been closed nevertheless)

New plants: The last of the demonstration projects was built in 1991 (Utrecht), and new plants have not been inaugurated before (late) 1998. From these three new plants, not much operational experience could be expected, but the incorporation of previous experience into the system design might be interesting.

The distinction between experiments and demonstration sometimes is not very sharp; Le Plaisir for instance was intended to become a demonstration plant after an experimental phase, but due to the problems encountered this never was realized. Table 3 shows the number of projects for the different categories and storage types.

Table 1 Number of reviewed projects

Total 22 projects	ATES	BTES	CTES
Experiment	4	4	0
Demonstration	3	5	3
New plants	2	1	0

An overview of all reviewed projects, divided into the three storage types, is given in the following tables.

Table 2 High Temperature ATES plants

Year	Name/Location	Remarks
1976	Auburn Univ. Aquifer Storage Field Experiment, Mobile Al., USA	Experiments with warm water injection into aquifer, heat from power plant, later from oil boiler, closed
1987	Le Plaisir, Thiverval-Grignon, France	Experiments with very high temperature ATES, heat from incineration plant, closed
1988	Lomma Pilot ATES Plant, Lomma, Sweden	Small experiment for water chemistry, scaling and corrosion, closed
1982	University of Minnesota ATES Field Test Facility, St. Paul, USA	Experiment with ATES cycles at high temperature, heat from steam plant, closed
1982	SPEOS, Lausanne-Dorigny, Switzerland	Experiments and heat supply to buildings, test site for water treatment methods, closed
1982	Hørsholm, Denmark	Experiments, heat supply to district heat, heat from waste incineration, closed
1991	De Uithof, Utrecht University, Utrecht, The Netherlands	Waste heat from heat and power co-generation, serves campus, still in operation
1998	Reichstag building and offices, Berlin, Germany	Waste heat from heat and power co-generation, large net, in operation
1998	Hospital "Hooge Burch", Gouda, The Netherlands	Waste heat from co-generation, in operation

Table 3 Main data of High Temperature ATES plants

Project	Storage loading temp.	Storage un-loading temp.	No. and depth of wells	Flowrate m^3/h	Capacity
Auburn 1976	37-55 °C		2 / ca. 60 m	22-90 m^3/h	Experiment
Auburn 1978	59-88 °C		1 / ca. 60 m + 1 shallow	?	Experiment
Le Plaisir	55-180 °C		1+3 / 500 m	90 / 120 m^3/h	Experiment
Lomma I	37-82 °C	60-19 °C	2 / 35+42 m	1.7-1.8 m^3/h	Experiment
St. Paul	89-131 °C	89-59 °C	2 / ca. 240 m	45-66 m^3/h	Experiment
Dorigny	50-80 °C	60-30 °C	horizontal *	ca. 10 m^3/h	~500 MWh
Hørsholm	100 °C	90-63 °C	1+4 / 25 m	15-60 m^3/h	>1 GWh**
Utrecht	90 °C		2 / 260 m	100 / 50 m^3/h	<2 GWh
Berlin	70 °C	60-20 °C	2 / 320 m	100 m^3/h	
Gouda					

* 2 sets of horizontal drains 7 and 24 m deep, connected to central access shaft

** Maximum unloading achieved was 159 MWh/a

Table 4 High Temperature BTES Plants

Year	Name/Location	Remarks
1982	Seasonal ground storage system, EU Joint Research Center, Ispra, Italy	Experiment with seasonal cycles, heat from solar collectors, probably closed
1981	Borehole Heat Store Experimental plant, Luleå, Sweden	Experiments for thermal behaviour of borehole store, closed
1986	Versuchsanlage Rümlang, Switzerland	Small experiment to study interaction between boreholes, heat from oil boiler, closed
1992	SGI heat storage tests in clay, Linköping, Sweden	Experiments to investigate heat storage in clay, heat from el. boiler, probably still in operation
1989	Cormontreuil, France	Small store fore solar heat, closed
1984	CSHPSS, Groningen, The Netherlands	Large solar heat store, 2 cycles monitored, supplies heat to houses, still in operation
1983	Kullavik, Sweden	Large solar heat store with low and high temperature zone, supplies heat to houses, still in operation as low temperature store
1983	Lulevärme Borehole Heat Store Demonstration Plant, Luleå, Sweden	Large store for excess heat from co-generation, monitoring, optimization, closed
1983	Motorway maintenance center Vaulruz, Switzerland	Solar heat storage in horizontal pipes, relatively small, probably still in operation
1998	Residential area Amorbach, Neckarsulm, Germany	Solar Heat storage, modular extension concept, monitoring and experiments, in operation

Table 5 Main data of High Temperature BTES plants

Project	Storage loading temp.	Storage un-loading temp.	No. and depth of boreholes	Type of BHE	Capacity
Ispra	ca. 50 °C		36 / 10 m	Single-U	Experiment
Luleå I	ca. 55 °C		19 / 21 m	Open hole	Experiment
Rümlang	ca. 50 °C		7 / 24.5 m	Co-axial	Experiment
SGI store 1	35-70 °C		100 / 10 m	Single-U	Experiment
SGI store 2	70 °C		100 / 10 m	Single-U	Experiment
Cormontreuil	50-55 °C		20 / 15 m	Co-axial	38 MWh
Groningen	60 °C	50-30 °C	360 / 20 m	Single-U	>220 MWh
Kullavik	60 °C	50-40 °C	200 m^3 / 8 m	Single-U	4-8 MWh
Luleå II	70-82 °C	70-30 °C	120 / 65 m	Open hole	1 GWh
Vaulruz	54 °C	40-5 °C	horiz. pipes 1.6-6.2 m deep		~170 MWh
Neckarsulm	80 °C		168 / 30 m	Double-U	

2.4 Lessons Learned

2.4.1 ATES

A number of problems were encountered in HT-ATES plants, in particular in the temperature range ≥100 °C. The experiences from the individual plants are listed below.

Auburn:

1. Clogging of injection well (the water from the storage aquifer itself was not used for injection, but first water from power plant and then from a different, shallower aquifer)
2. Failure of confining layer around an abandoned well in the area
3. Problems with heat extraction due to buoyancy flow

Le Plaisir-Thiverval-Grignon

1. First water treatment system (with lime) not satisfactory
2. No problems in test with up to 55 °C loading temperature
3. Injection up to 180 °C successful, but unloading impossible:
    a. Poor well completion caused inflow of sand
    b. Special pump for extraction at very high temperature (180 °C) did not work properly
4. System damaged terminally during well recovery operation

Lomma I

1. No scaling without water treatment, attributed to natural inhibitors

St. Paul

1. Minor problems with ion exchange water treatment, in general satisfactory, but requiring huge amounts of salt (NaCl) for regeneration
2. Some problems with pumps while unloading
3. Minor problems with buoyancy flow
4. Experiments and pilot operation successful

Dorigny

1. Clogging of horizontal drains and scaling in heat exchangers (scaling later could be solved by using a fluidized bed heat exchanger)
2. First strategy (storing in upper layer) caused higher losses, later reversed (storing in lower layer)
3. Transfer from experimental/demonstration phase into commercial phase failed

Hørsholm

1. Many operational problems (valves, pressure sensors, pumps)
2. DH return temperature mostly to high for efficient unloading of store
3. Problems with rupture in the top confining layer
4. No complete loading/unloading cycle achieved, and no transfer into commercial phase

Utrecht

1. System works well with respect to co-generation waste heat disposal, but users were not aware of efficiency of storage operation
2. Return temperature from buildings was too high, thus minimum design unloading temperature was not met and unloading of the store was less than designed.
3. Energy demand at lower temperature level was not as high as in the design.
4. Problems with control system (later upgraded by user), deep shaft pumps and control of water treatment system
5. Clogging of one well in 1997 while water treatment system did not work

Berlin

1. Design tools (numerical simulation) used widely
2. First test operation successful, no further experience yet

Gouda

1. No operational experience reported

Summary of Main ATES Operational Issues

A general problem reported were higher than required supply temperatures to the user than expected and lower unloading temperature of the store due to unexpected buoyancy flow.

Main areas of technical problems were:

1. Control system
2. Deep shaft pumps and other special pumps (better to use submersible pumps, if available)
3. Frequency controllers with long cables (electromagnetic noise)
4. Sensors (in particular flow meters)
5. Cracking of confining layer due to high pressure
6. Corrosion, if material is not adequate
7. Well clogging problems due to inadequate or not working (Utrecht!) water treatment system.
8. Models worked well for prediction of storage behaviour, after buoyancy flow problem was understood.

Experiences with Water Treatment:

1. Fe/Mn-treatment: The only possibility is to keep the system under pressure. If mixing in the ground is possible, no ATES should be built.
2. Gas clogging: The only possibility is to keep the system under pressure; degassing units may also be a solution.
3. Carbonate treatment: A selection of methods is available, like Na^+ ion exchange, addition of acids (NaCl, but no HNO_3, H_3PO_4 or H_2SO_4, which may act as nutrients for bacteria), addition of CO_2, or the fluidized bed heat exchanger. Only Na^+ ion exchange and addition of HCl were used successfully in full-scale plants.

2.4.2 BTES

With BTES, many fewer operational problems occurred, but thermal behavior was not always good. The individual experiences are:

Ispra

1. Storage too small for direct heating, mostly used through heat pump
2. Reliability of operation satisfactory

Luleå I

1. Some minor operational problems (cooling phase), small-scale experiment successfully matched simulation data

Rümlang

1. No operational problems reported, data used for model validation

SGI-Linköping:

1. Both HT-stores operated for experiment as planned
2. Surface settlements of clay store 72-88 mm

Cormontreuil:

1. Problems with leakage (outer, thin membrane of coaxial BHE)
2. Moisture movement in chalk not considered
3. Management problems, too many people involved

Groningen

1. Main problems with solar collectors in the beginning
2. Heat losses of store 1.6 times higher than calculated (groundwater movement, lower thermal resistance of top insulation, higher storage unloading temperature)
3. Commercial operation without major problems, but with lower energy savings than expected

Kullavik

1. No operational problems in HT-store
2. Solar collector efficiency lower, reducing use of HT-zone of the store; eventually converted to part of LT-zone

Luleå II

1. The predicted storage efficiency was not achieved in the first year, the reason was a construction error with the de-aeration system. After fixing, only minor problems occurred due to a control error in the heat exchanger flow.
2. Problems with operation and maintenance of heat pumps
3. Surface connections (pipes) not optimum design
4. Thermal fracturing of rock observed

Vaulruz

1. The project worked as expected, but needs heat pump a lot for unloading

Neckarsulm

1. Design tools used widely
2. Borehole diameter and U-pipe shank spacing to small in first experimental store, heat transfer lower than expected; upgraded for completion of the store
3. No further operational experience yet

2.4.3 Summary of Lessons Learnt

The lessons learned (and to be observed for future work) are:

1. An exact prediction of the whole system characteristics is important in the design phase. In the demonstration plants, energy demand was mostly not as designed, affecting storage efficiency.
2. User behavior plays a critical role in the operation. Sometimes a user made changes to operations without consulting the designer (user interference was mostly beneficial, e.g. in Utrecht). On the long term, user interference should be limited, to prevent errors.
3. Even if systems run without major problems, users usually do not know if they run at optimum efficiency or even well. Hence, monitoring and evaluation is crucial to find the flaws in system design, construction, and operation. Minimum monitoring required is temperatures, water and energy flows in the surface installation over a period of at least 2 cycles. It should be investigated, if monitoring can serve as an early warning system.
4. For ATES, effective water treatment is a crucial issue. The systems used in the full-scale demonstration plants proved effective, but had serious disadvantages. Methods used in hydro-geothermal energy use (air tightness, additional pressurizing with N_2, as done for the Berlin project) and new water treatment methods have to be tested in full scale.
5. Storage of high temperatures close to 100 °C is risky in shallow aquifers, as ruptures in top confining layers due to high injection pressures showed (Auburn, 40 m overburden, and Hørsholm, 10 m overburden).

2.5 Chemical and Environmental Aspects

Chemical and environmental aspects were treated in Annex 6 of the IEA Energy Storage Programme. The aim of the Annex 6 research was to develop effective and environmentally sound water treatment methods to be used in combination with heat storage in aquifers, especially at high temperatures. This aim first required a better insight to be obtained into the geochemical and microbiological processes involved in aquifer thermal energy storage (ATES). The IEA ECES Annex 6 started in 1986. The research (laboratory, technical scale and field tests) started in 1987.

The main conclusions of the geochemical research can be summarized as follows:

1. Operationally problems at ATES projects due to geochemical processes were mostly caused by the precipitation of carbonates and/or the precipitation of iron/manganese hydroxide.

2. Problems due to the precipitation of silicates have not been observed at ATES projects and are not expected if the groundwater temperature does not exceed a temperature of approx. 100 °C.
3. Precipitation of carbonates occurs when the groundwater temperature rises. The laboratory experiments demonstrated, that carbonate precipitation is inhibited by various substances, such as organic acids and orthophosphates. These inhibitors are often naturally found in aquifers. This implies that water treatment needs not to be so intensive to prevent carbonate precipitation.
4. In several cases, cation exchange processes play a major role in explaining changes in water composition. These processes can be modeled adequately (APPELO et al., 1990b).
5. Precipitation of iron/manganese hydroxide is not caused by a change in temperature, but by a change in water composition. The main causes are (ANDERSSON, 1990):
   - contact to air
   - mixing of waters differing in redox status upon entering the wells
   - escape of carbon dioxide from the water and increasing of the pH value

These precipitations can be avoided by an appropriate design and operation of the plants.

Thermal energy storage in an aquifer leads to changes of the geochemical properties, mainly by dissolving and precipitating minerals. These processes lead to environmental changes, especially for autochthonous bacteria and other microorganisms.

If an aquifer is used, which is contaminated by pathogens and/or opportunistic pathogens, human exposure to these microorganisms could occur by ingestion of the water or by inhalation of aerosols, i.e. when such aerosols are generated by cooling towers in the vicinity of human activities. Microorganisms within the circulating system of an operational ATES plant live in the water or as biofilms on surfaces. They may lead to biofouling, especially of heat exchangers, or to microbiologically induced corrosion (MIC) (ADINOLFI et al., 1990; WAGNER et al., 1988, FLEMMING, 1992).

The following problems were treated within the IEA task:

1. Biochemical reactions, like the precipitation of iron/manganese hydroxide and anaerobic metal corrosion (microbially induced corrosion).
2. Biofouling of wells and heat exchangers due to excessive bacterial growth
3. Major modification of the aquifer bacterial flora with adverse environmental impacts
4. Development of (opportunistic) pathogenic microorganisms in the aquifer and in the installations.

The local changes of the subsurface and surface environment have the potential for creating four broad biochemical, geological and microbiological phenomena

1. Conditioning of surfaces by microorganisms prior to scaling; biofouling on aquifer material and heat exchangers
2. Clogging by inorganic scales in aquifers, wells and drains
3. Clogging by corrosion products in wells and drains
4. Microbially induced corrosion (MIC)

2.5.1 Water Treatment Research

The main aspects of water treatment research can be outlined as follows:

1. Well clogging caused by precipitation of iron/manganese hydroxide occurs when the groundwater contains dissolved iron and/or manganese and either air (oxygen) can enter the ATES installation somewhere (clogging of infiltration well), or at the same time groundwater with a high redox potential is extracted (clogging of production well). Furthermore, clogging of infiltration wells appears to be possible by fines (silt, clay etc.) and gas bubbles. The fines practically always originate from the production well(s) because of inadequate development or damage. Gas clogging may occur as a result of gases present in the groundwater coming out of solution, caused by a decrease in pressure of the groundwater in the ATES installation.
2. Scaling due to carbonates is the most common form of scaling in ATES systems. Not only because of temperature rise of the groundwater can carbonate scaling occur, but also because of the escape of CO_2 from the groundwater. The inhibition by polyorganic substances and orthophosphates, mentioned above was confirmed by the scaling experiments, as follows: no carbonate scaling was found in the experiments carried out at the Lomma ATES project in Sweden, though scaling was expected because of oversaturation of the groundwater with respect to carbonates.
3. Both chemical and electrochemical corrosion occur in ATES installations. Chemical corrosion is induced by constituents such as CO_2, O_2, H_2S, dissolved sulfide, chloride and sulfate. The most common cause of corrosion in ATES- connected systems is due to the unplanned entry of air (oxygen). Sites that have used HCl to remove or prevent carbonate precipitation have experienced significant corrosion. Many ground waters in confined aquifers have a reduced state (low redox potential). On the one hand, this means that the problems due to chemical corrosion are generally smaller than with oxygenated groundwater. On the other hand, this means that most of the literature on corrosion does not apply to ATES installations. Electrochemical corrosion is caused mainly by joining metals with different electrochemical potentials. This can be avoided by a proper selection of materials.

The research has indicated that most operational problems caused by clogging, scaling and corrosion can be predicted and avoided by appropriate design, construction and operation of the ATES system, or with the help of suitable water treatment methods.

The research on water treatment methods for ATES was started by examining the conventional water treatment methods intended to prevent precipitation of carbonates and of iron/manganese hydroxide and to de-aerate water. It was found that, if these are to be used for ATES projects, a number of specific limiting conditions have to be met.

The environmental impact resulting from water treatment needs to be very small, because the treated water is infiltrated into the aquifer and partly spreads downstream of the store. For instance, an increase in the chloride concentration due to HCl treatment may render fresh water unsuitable for human consumption (Willemsen, 1990).

On the basis of the evaluation of the above criteria, only a limited number of conventional water treatment methods appear to be suitable to be applied to ATES Systems (Subtask C Report by Greulich et al., 1991).

2.6 Operational experiences from existing HT-UTES-plants

This section provides a summary of the operational experiences from existing HT-UTES –Plants.

2.6.1 General remarks

1. In commercial systems, users usually do not know if they run at optimum or even well.
2. Monitoring and evaluation is crucial to find the flaws in system design, construction, and operation.
3. in the long term, user interference should be limited, to prevent errors.
4. Good to optimum operation is required for long-term sustainable performance.
5. In demonstration plants, energy demand was mostly not as designed, affecting storage efficiency.

2.6.2 User behavior:

1. Users commonly change without consulting or informing the designer
2. On the other hand, user interference was mostly beneficial (e.g. in Utrecht).
3. User education is crucial!

2.6.3 Monitoring:

1. Minimum requirements are temperature, water and energy flows in the surface installation
2. Minimum monitoring period is at least 2 cycles.
3. (Monitoring as an early warning system?

2.6.4 Storage efficiency and temperature:

1. General: Unloading temperature can be lower due to unexpected buoyancy flow.
2. Luleå: The predicted storage efficiency was not achieved in the first year, the reason was a construction error with the de-aeration system. After fixing, only minor problems occurred due to a control error in the heat exchanger flow.
3. Utrecht: Return temperature from buildings was too high, thus minimum design unloading temperature was not met and unloading of the store was less than designed. Energy demand at lower temperature level was not as high as in the design.

2.6.5 Main technical problems

1. Control system (in Utrecht later upgraded by user)
2. Deep shaft pumps (better to use submersible pumps)
3. Frequency controllers with long cables (electromagnetic noise)
4. Sensors (in particular flow meters)
5. Surface connections (pipes)
6. Problems with Heat Pumps (e.g. in Luleå)
7. Cracking of confining layer due to high pressure
8. Corrosion, if material is not adequate
9. Well clogging problems due to inadequate or malfunctioning water treatment system (Utrecht).

2.6.6 Experiences with water treatment

1. Fe/Mn-treatment: The only solution is to keep the system under pressure. If mixing in the ground is possible, no ATES should be built.
2. Gas clogging: The only solution is to keep the system under pressure, although degassing units may also be a solution.
3. Carbonate treatment: A selection of methods is available, like Na+ ion exchange, addition of acids (NaCl, but no HNO3, H3PO4 or H2SO4, which may act as nutrients for bacteria), addition of CO2, or the fluidized bed heat exchanger. Only Na+ ion exchange and addition of NaCl were used successfully in full-scale plants.

2.7 System opportunities and chances for increased application of HT-UTES

2.7.1 Possible heat sources

The following offer opportunities for heat storage in the ground

1. Heat and power co-generation (only with high electrical efficiency and/ or electricity led power generation)
2. Industrial / process heat (paper mills, steel works, and others)
3. Waste incineration
4. Load leveling in district heating systems (short- to medium term)

The overall efficiency of the HT-UTES systems can be improved where there is also the potential to integrate geological heat storage with renewable energy technologies where heat generation does not always coincide with demand, e.g.:

1. Solar thermal (solar collectors, but also road surfaces etc.)
2. Geothermal (hydrogeothermal, but also waste heat from geothermal power plants, e.g. Hot Dry Rock)
3. Others (biofuels?)

2.7.2 Possible heat users

There are various demand scenarious that can be considered that will provide improved diversification of the heat load and improve the district and regional economics for both district heating and heat storage. Some examples are as follows:

1. Space heating
   a. District heating
   b. Large buildings (housing, offices, hospitals, hotels, airports, etc)

2. Industrial heat
   a. Batch or seasonal processes like in sugar refineries
   b. Drying in food industry
   c. Most industries have excess heat, and therefore have no requirement for UTES

3. Agriculture
   a. Greenhouse heating
   b. Drying of grain, hemp, grass (hay), etc.
   c. Aquaculture
   d. De-icing and snow-melting on roads, sport centers, airports/runways, etc.

2.8 Geological Closed Loop Characteristics and Terminology

Two of the most pertinent points of reference for closed loop systems include Eskilson (1987) and Hellstrom (1991). Although these texts almost solely concern the simulation of vertical systems they nevertheless confirm the main parameters that must be considered for all closed loop systems. Prior to this work at Lund University in Sweden, significant publications included Ingersoll (1955) and Carslaw (1959) which developed basic heat conduction theory that could be applied to this approach.

When designing a closed loop BTES there is an inevitable requirement to analyse the interaction characteristics of the heat pump and the ground. It is clear that the design of the ground loop heat exchanger (GLHE) must enable the heat pump to run to an acceptable performance level and also within safe limits specified by the manufacturer. Therefore, the temperature and flow rate of the fluid must not fall below (in heating mode) or rise above (in cooling mode) pre-determined limits.

Eskilson (1987) analysed three key parameters that must be considered to ensure the GLHE is designed correctly. These include the thermal conductivity, the borehole resistance and the ground temperature. Other less significant factors include the bulk volumetric heat capacity, considered in more detail in the work on ground heat storage by Hellstrom (1991), and the necessary existence of turbulent flow within the GLHE to maximise heat transfer (Eskilson, 1987).

Definitions:

Thermal Conductivity; λ, (W/m.K} - the ease at which heat travels through the ground.

Volumetric Specific Heat Capacity, $\rho_g c_g$ (kJ/m^3.K) – the thermal heat capacity of the ground by volume.

Borehole Resistance; R_b [K/(W/m)] – the thermal resistance between the circulating fluid and the ground

Ground Temperature: T [°C] – this can be defined as the far field or undisturbed temperature.

Thermal conductivity and the specific heat capacity are interrelated by the thermal diffusivity,α, shown in [1].

$$\alpha = \frac{\lambda}{(\rho c)_g} \qquad [\,1\,]$$

The diffusivity hence becomes a measure of the ground's capability to conduct thermal energy relative to its ability to store thermal energy.

Eskilson (1987) approached the vertical closed loop solution for fluid temperature, T, as a function of the radial distance (r), the depth below ground (x) and time (t), and using the base cylindrical heat conduction equation **[2]**. The thermal conductivity and specific heat capacity are both considered by way of the inclusion of the thermal diffusivity.

$$\frac{1}{\alpha}\cdot\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial x^2} \qquad [\,2\,]$$

∝	Thermal diffusivity (m²/s)
T	Ground Temperature (˚C)
t	Time (s)
r	Radial distance (m)
x	Depth beneath ground (m)

Equation **[2]** was further developed adopting a corrective factor for the borehole resistance, to calculate the temperature on contact to the carrier fluid.

The primary work by Hellstrom (1991) and Eskilson (1987) focuses on the transport of heat by conduction in the solid material and groundwater. Heat transport by advection, i.e. groundwater flow, is neglected as it is site specific and, therefore, too difficult to generalise. Hellstrom does accept that high permeability soils and rocks could be affected by advection, and work by Chiasson (2000) investigated this further. The conclusions suggest that sites underlain by unconsolidated sands and gravels and highly fissured rocks exhibiting high hydraulic gradient would be affected. In such conditions advective heat transfer could help to naturally recharge the area in heating or cooling dominated loads. Conversely, if there is strategic preference to seasonally store heat or coolth, the existence of significant groundwater flow would reduce the recovery efficiency. The analysis requires site by site consideration to review the hydraulic gradient.

2.8.1 Thermal Conductivity and Specific Heat Capacity of Soils and Bedrocks

The thermal conductivity and volumetric specific heat capacity of a soil or rock is determined by the mineral content, the porosity and the saturation (Eskilson, 1987) . Clauser provides a detailed presentation of both theory and data on the thermal properties of different minerals, formations and saturated geomaterial (1995; 2007).

The thermal conductivity of a number of common relevant minerals is shown in Table 6. The range in values is significant not just between minerals but also according to the exact structure, density and anisotropy of the same mineral. This help to explain the large range in values for the different minerals. The impact of saturation in higher porosity geology is then indicated by the relative thermal conductivity values of water and air, and the proportion and value of the solid material.

Table 6 Example thermal conductivities of common minerals

Mineral	*Thermal Conductivity, λ (W/mK)*	*Temperature (˚C)*	*Reference*
Diamond	895-1350	27˚C	(Clauser, 2007)
Quartz	3.52-10.2		(Clauser, 2007)
Calcite	3.16-3.63		(Clauser, 2007)
Feldspar: e.g.			
- Albite	2.34	25˚C	(Clauser, 2007)
- Anorthite	2.72	25˚C	(Clauser, 2007)
Water	~0.6	10˚C	(Rogers and Mayhew, 1995)
Air	~0.02	10˚C	(Rogers and Mayhew, 1995)

To demonstrate the variance in thermal conductivity due to mineral content, the example of quartz content in plutonic rock is shown in Figure 2. The exact concentration of the quartz in the rock is not known for each of the samples but the range in values provides a good indication of the distinct influence in this type of rock. Equally, and to demonstrate the influence of porosity, Figure 3 shows the difference in thermal conductivity for low porosity and high porosity volcanic rocks. Here, high porosity rock has a lower thermal conductivity due to the greater percentage of water and/or air by volume.

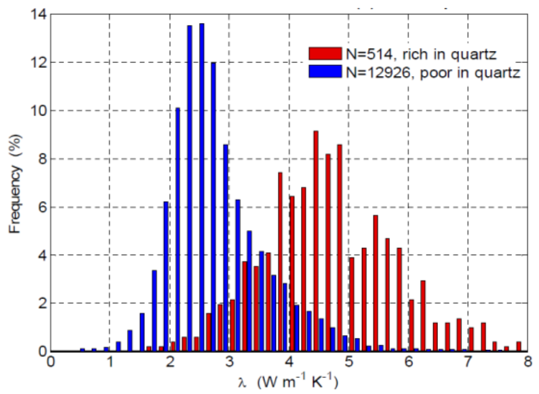

Figure 2 Variance of thermal conductivity of plutonic rocks according to quartz content (Clauser, 2007).

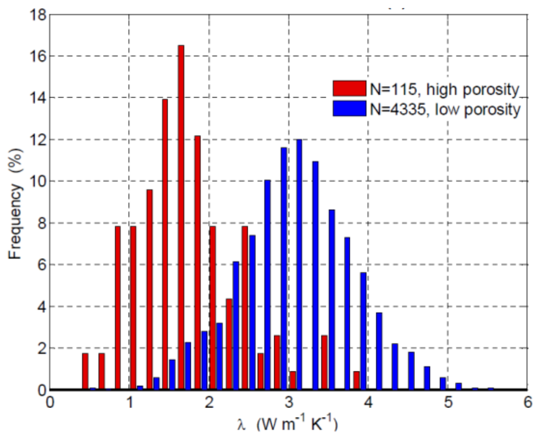

Figure 3 Variance in thermal conductivity according to porosity in volcanic rocks (Clauser, 2007)

The thermal conductivity of a bedrock and soil can also vary according due to anisotropy i.e. the measured thermal conductivity may vary according to the axis of measurement. This is less prominent in igneous rocks but can be significant in sedimentary and metamorphic rocks. Clauser also provides a good summary of data collected in this area (Clauser, 2007).

It is clear that there are inherent problems in specifying typical values for thermal conductivity for different geomaterials and site specific conditions. Indeed, there is a strong justification to conduct in-situ thermal response tests for every installation to improve accuracy prior to completing the design of a ground loop heat exchanger (Eskilson, 1987). However, at the start of the design process when no such test has been carried out there is still a need for “typical” values to be used. Also, since the test itself can be costly it may not be justified to carry out such a test for smaller domestic systems, rather it may be more cost effective to apply some form of safety factor (Banks, 2008).

The German Institute of Engineers has provided typical values in guidance documents (VDI, 2001). These values concur with data sets presented by Bose (1985), Sundberg (1988), referenced in both sets of work by Eskilson (1987) and Hellstrom (1991), and also Clauser (1995). Using the VDI guidance the potential range for the thermal conductivity for the more prominent rocks and soils are shown in Figure 4 and Figure 5. The range in values for each geomaterial is now known to be a function of the specific mineral content and concentration, porosity and water saturation but it is also probable that the range also reflects the number of samples taken for each type.

Sandstone, in particular, has a wide potential range in thermal conductivity. Most sand grains are composed of quartz (Blyth and de Freitas, 1984) although the cementation can vary considerably by mineral type. For example, siliceous sandstones are cemented with quartz or cryptocrystalline silica whereas ferroginous sandstones are cemented with iron oxides such as haematite and calcareous sandstones, calcite. As stated in Table 6 Quartz has a thermal conductivity of 3.5-10.2W/mK whereas Haematite can be much higher at 12.4W/mK (Clark Jr., 1966) and calcite lower at ~3.2 (Popov et al., 1999). The thermal conductivity of the differing cementing minerals, combined with differing porosity and moisture content suggests why there is such a range in thermal conductivity for sandstones. Hence, similar differing mineral content and porosity for other bedrock types will result in a range in thermal conductivity. A good example of the impact of porosity is shown in the difference between the typical range for sandstone and meta-quartzite. In both cases the main mineral constituent is quartz but the values for meta-quartzite are shown to be higher. Meta-quartzite has a much lower porosity. The rock has also metamorphosed providing an improved thermal conductivity due to the recrystallined structure which is a very compact quartzite.

Without knowing more information about the samples taken it is difficult to discuss in detail the reason for the absolute range for each bedrock and superficial deposit. At the time of writing the guidance provided by VDI (2001) seems to be the most applicable and widely accepted reference for the specific design of closed loop systems. There is limited data available for specific UK geology, such examples include work published by the BGS (Rollin, 1987) which provides some data for certain lithologies but the spatial coverage is limited.

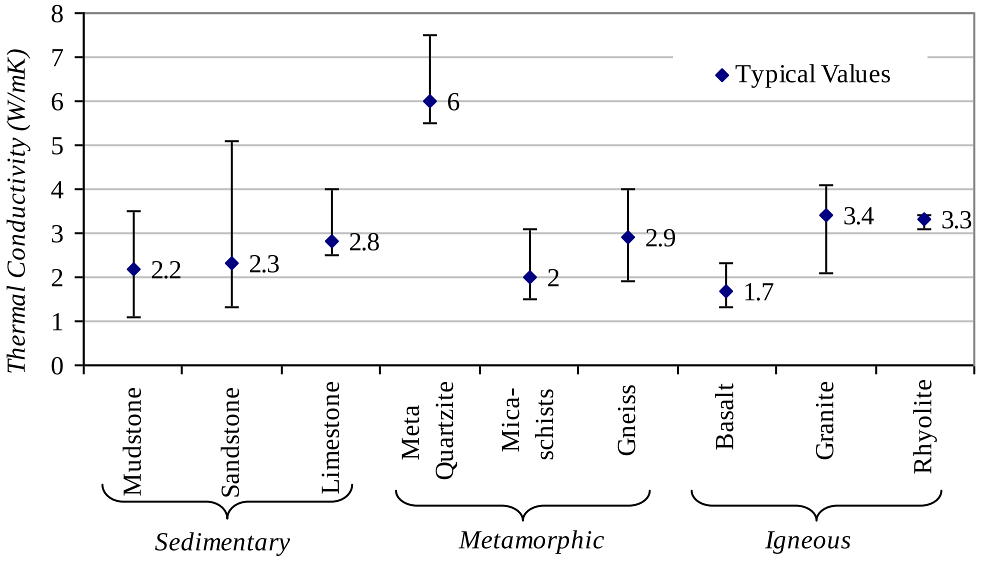

Figure 4 Thermal conductivity for different bedrock types (VDI, 2000)

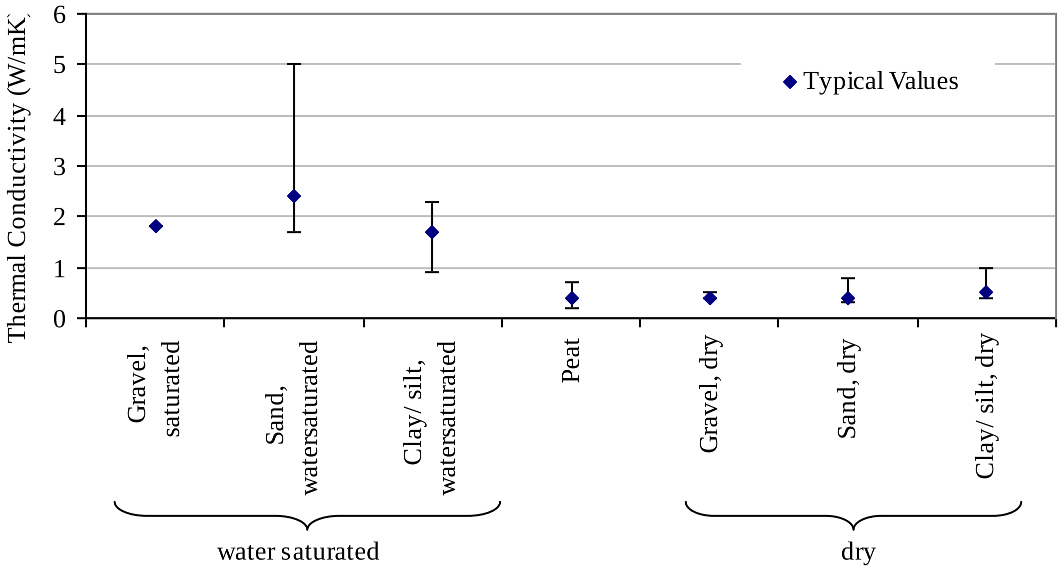

Figure 5 Thermal conductivity for superficial deposits (VDI, 2000)

On first glance there are similar complexities with generalising the specific heat capacity although this parameter is not now influenced by anisotropic tendencies. The range in heat capacity for different minerals is also less pronounced although the effect of porosity and saturation is still significant (Clauser, 2007). This can be understood by reviewing the respective heat capacities for water, which is 4.15 MJ/m^{3}K at 10°C, and dry air, at the same temperature, is much lower at 0.0012 MJ/m^{3}K (Rogers and Mayhew, 1995).

Using Kopp's Law and assuming full saturation of the ground the volumetric heat capacity can be approximated using equation [3].

$$(\rho_g c_g) = (1-\phi)(\rho_s c_s) + \phi(\rho_w c_w) \qquad [\,3\,]\ \text{(Schaetzle et al., 1980)}$$

ϕ	Porosity (-)
$\rho_{g,s,w}$	Density: ground, solid material, water (kg/m^3)
$c_{g,s,w}$	Specific heat capacity: ground, solid material, water (kJ/kgK)

The volumetric heat capacity for bedrock is shown in Figure 6. The quoted range in typical values for bedrock is apparently non existent or small, with most rock exhibiting a volumetric heat capacity of 2100-2250 kJ/m^3.K. Granite and Basalt are noted to be particularly high at 2450 and 2550kJ/m^3.K. The suggested reason for this is that, although the porosity is low, the bulk density assumed in the calculation is higher than used in the other rock calculations thereby increasing the volumetric heat capacity. The results also suggest that few samples have been measured.

Water has a higher specific heat capacity than all minerals so in saturated lithology a high porosity and moisture content can improve the specific heat capacity. Certain bedrocks exhibiting high ranges of porosity are therefore likely to produce corresponding differences in volumetric heat capacity. The data set published by the VDI does not show variation for certain bedrocks which either suggests a small data set and/or consistent porosity for test sample.

The effect of saturation is demonstrated by analysing the available data for superficial deposits. The suggested range in volumetric heat capacity for superficial deposits is led by peat which has a suggested range of 500 kJ/m^{3}K, for dry peat, to ~3800 kJ/m^{3}K for higher porosity, saturated peat. For saturated superficial deposits the variance is less pronounced however, with low porosity clays having a heat capacity of 1600 kJ/m^{3}K to high porosity clays at 3400 kJ/m^{3}K.

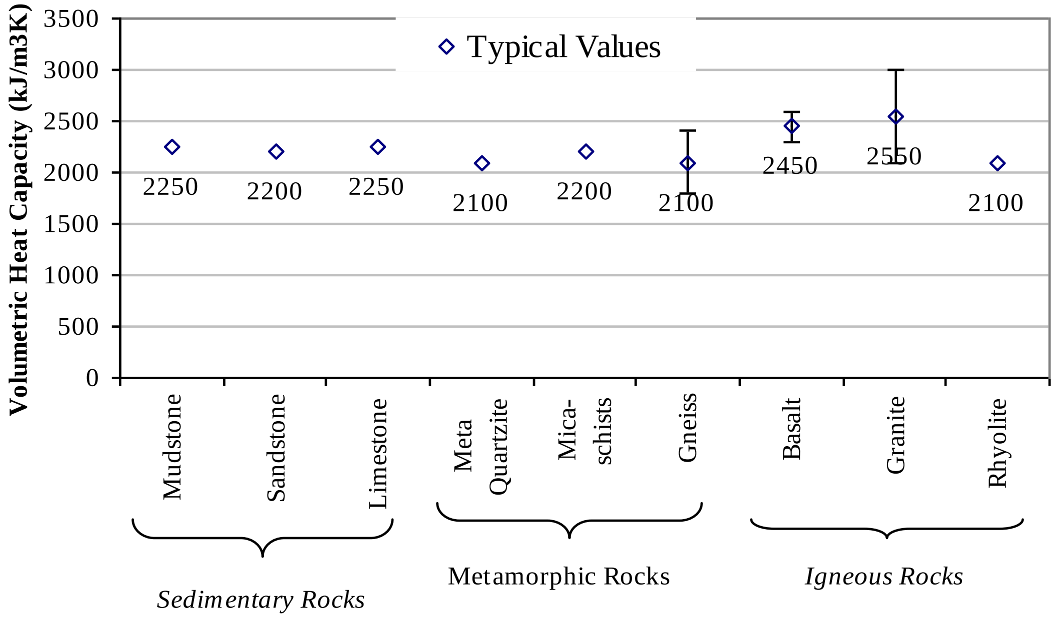

Figure 6 Volumetric Heat Capacity for main bedrocks (VDI, 2000)

2.8.2 Borehole Thermal Resistance Description

Eskilson (1987) presented the basic equation for borehole thermal resistance, R_b [4]. The heat transfer rate is governed by the difference in temperature between the carrier fluid in the borehole and the ground temperature, and the thermal borehole resistance between the two. It therefore becomes important to reduce the borehole resistance within the limits of cost and practicability.

$$q = \frac{T_b - T_f}{R_b} \qquad [4]$$

q	Heat transfer rate (W/m)
$T_{b,f}$	Temperature: b=outer borehole temperature, i.e. the ground. (˚C) f=carrier fluid (˚C)
R_b	Borehole resistance K/(W/m)

In vertical systems, the borehole thermal resistance is a function of the thermal conductivity of the pipe wall, grout and the flow regime in the pipe, but also the distance of the circulating fluid to the ground.

2.8.3 Ground Temperature

The undisturbed ground temperature within the region of interest for vertical systems is inherently linked to the air temperature. Table 7 below provides an overview of the average annual air temperatures throughout the UK from 2002-2007. The mean temperature is 9.6˚C. The minimum is in North Scotland at 7.8˚C and the maximum in East Anglia, the South East and Southern England at 10.9˚C.

Table 7 Average annual air temperature throughout the UK (Met. Office, 2008)

Region	**Mean Temperature 2002-2007 (˚C)**
UK	**9.6**
England	10.4
Wales	9.8
Scotland	8.2
N Ireland	9.6
Scotland N	*7.9*
Scotland E	*8.0*
Scotland W	*8.9*
England E and NE	*9.7*
England NW and Wales N	*9.6*
Midlands	*10.2*
East Anglia	*10.9*
England SW and Wales S	*10.4*
England SE and central S	*10.9*

The ground temperature nearer the surface can fluctuate throughout the year according to depth. To calculate the temperature nearer the surface, Carslaw and Jaeger (1959) derived the following equation [5]:

$$T_{wall}(x,t) = T_m - T_{amp}\, e^{\left[-x(\pi/365\alpha)^{1/2}\right]} \cos\left[2\pi/365\left(t - t_o - x/2(365/\pi\alpha)^{1/2}\right)\right] \qquad [5]$$

$T(x,t)$	undisturbed ground temperature (˚C)

T_m	mean annual temperature at the ground surface (˚C)
T_{amp}	amplitude of the temperature fluctuation at the ground surface (K)
x	depth below ground level (m)
α	soil thermal diffusivity (m^2/s)
t	Time (0-8760hrs)
t_0	phase lag (hrs)

By assuming typical values for the UK it is possible to plot the temperature at different depths throughout the year. An example set of profiles is shown in Figure 7. The values used in [5] are as follows:

T_m	10°C
A_s	8K
x	0, 1.0, 2.5 and 5m. below ground level
α	$0.001 m^2/s$ [$(\rho c)_g$ = 2,000kJ/m^3.K, λ=2W/mK]
t	0-8760hrs
t_0	1hr = 1st of January: time of lowest temperature

At a depth of 1m the temperature fluctuates between 5.7 and 14.3˚C compared to the surface variation of 2.4 to 17.6˚C. With depth the temperature amplitude reduces considerably where, in this example, the fluctuation is negligible at 5m below ground level. A higher thermal conductivity and low specific heat capacity can increase the amplitude at depth relative to geology with a lower conductivity and high specific heat capacity.

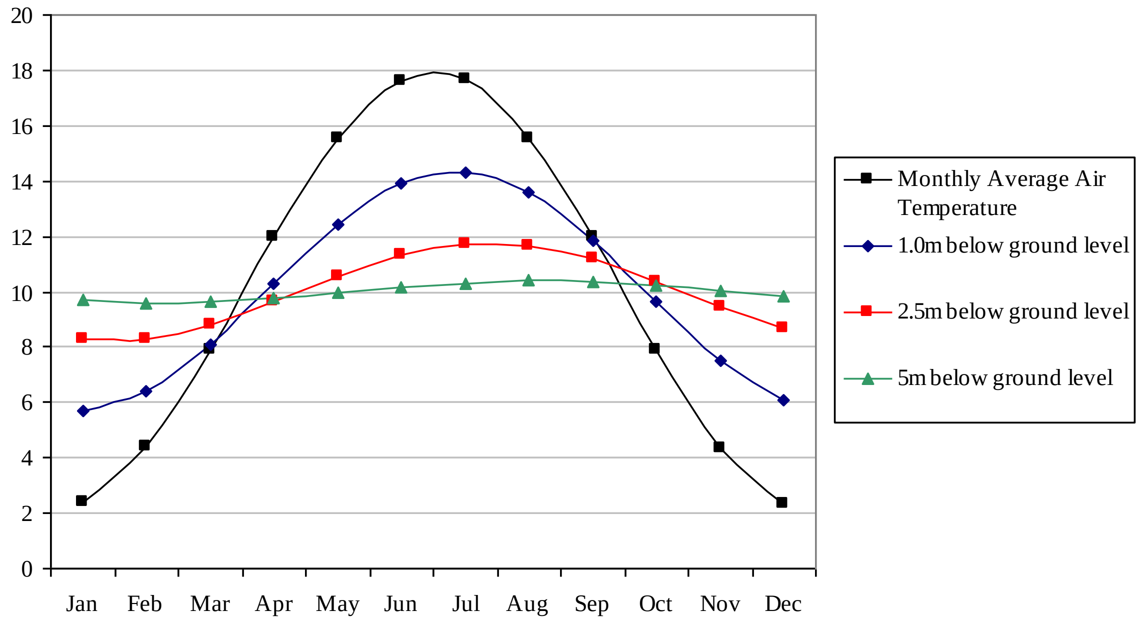

Figure 7 Example Fluctuation in ground temperature with depth

For vertical systems the undisturbed ground temperature at a certain depth is a function of the average annual air temperature and thermal gradient (Eskilson, 1987). The typical length of a vertical system is >40m; therefore any temperature fluctuations in the near surface geology will have a negligible effect on the bulk borehole temperature (Eskilson, 1987).

The thermal gradient can be calculated using Fourier's law.

$$\lambda = \frac{Q}{A\left(\frac{d\theta}{dx}\right)}$$

λ	Thermal Conductivity (W/mK)
Q	Heat flux (W/m)
A	Area (m^2)
$\left(\frac{d\theta}{dx}\right)$	Thermal gradient (K/m)

This can be transposed to give the thermal gradient, equation.

$$\frac{d\theta}{dx} = \frac{Q}{A\lambda}$$

Therefore, the thermal gradient is a function of the heat flux (Q/A) and the thermal conductivity (λ).

2.9 Hydrogeological Open Loop Terminology and Characteristics

Most groundwater comes from rainwater and melting snow and is known as meteoric groundwater and reaches the aquifer by way of infiltration and percolation (Blyth and de Freitas, 1984). The groundwater then flows naturally towards rivers, lakes and the sea where upon evaporation occurs allowing for the consequent precipitation of water back to land mass. This is known as the hydrogeological cycle.

It is clear that the potential for an open loop scheme is initially dependent on the existence of an aquifer beneath the site. The simple definition of an aquifer is a body of rock or soil that holds water and can transmit water easily; those rock and soil bodies that do not transmit groundwater easily are termed aquicludes (Todd and Mays, 2005). The term aquitard has also become more common in place of aquicludes to define a stratum that exhibits less permeable geomaterial but water abstraction is nonetheless considered uneconomic.

A more useful definition of an aquifer in the well water industry is that "… an aquifer is permeable enough to yield economic quantities of water to wells, whereas aquicludes are not" (Freeze and Cherry, 1979). Taking this one stage further, and hence in the context of open loop systems, the aquifer must yield sufficient economic quantities to contribute to the heating and/ or cooling system in a development (Banks, 2008).

The key parameters to assess a groundwater resource in the first instance are the hydraulic conductivity, permeability, storativity and the transmissivity.

Hydraulic Conductivity (*K [m/s]);* the speed at which ground water passes through an aquifer

Intrinsic Permeability (k[m^2]); describes the hydraulic conductivity of the geo-material irrespective of the fluid

Specific Storage (S[m^3]) ; the volume of water that a specific area of aquifer releases with respect to a unit drop in head

Transmissivity (T[m^2/s]); the quantity of water that an aquifer of a certain thickness can transmit horizontally.

The derivation and interrelationship of the different terms is described in numerous texts (e.g. Blyth and de Freitas, 1984) and is beyond the scope and intentions of this literature review. Ultimately, the most important and overarching engineering and economic factor to assess for an open loop system is the actual possible yield from the aquifer (Kavanaugh and Rafferty, 1997; VDI, 2001).

There are two main types of aquifer; confined and unconfined. A confined aquifer is confined between two impermeable layers whereas an unconfined aquifer is an aquifer in which the water table forms the upper boundary (Freeze and Cherry, 1979). Also there are two main aquifer formations, consolidated fractured bedrock and unconsolidated deposits. Fractured bedrock systems are typified by chalk, sandstones and limestones and unconsolidated deposits, sands and gravels. Certain consolidated bedrock, such as sandstone, sometimes allow groundwater flow through the bedrock mass. Aquifers, as with all geological strata show differing levels of homogeneity so properties can vary considerably for the same geological type, e.g. limestone, from location to location and also, within a certain site boundary.

Groundwater is held in voids in the strata, as shown in Figure 8, in unconsolidated aquifers, and in Figure 9, for fractured bedrock systems. Well sorted unconsolidated or intergrannular aquifers often have more homogeneous properties than fractured bedrock aquifers where the occurrence of fractures or fissures follows a more random pattern. This latter point has relevance when completing a desktop study, and then during the design and construction phase as the yield becomes dependent on the intersection of the well screen with a number of fractures.

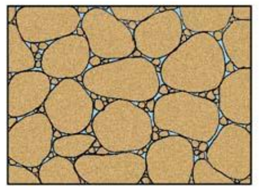

Figure 8 **Unconsolidated and Intergranular Aquifer System**

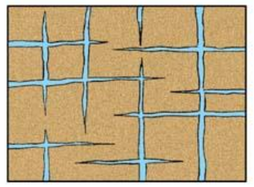

Figure 9 **Consolidated Fissured Bedrock Aquifer System**

An aquifer resource is often reviewed on 3 scales, a single well, the aquifer or the entire basin. The latter is not largely of concern for open loop schemes as this generally covers a very large geographical area.

Freeze and Cherry (1979) provide useful definitions of the well and aquifer yield:

Well Yield can be defined as the maximum pumping rate that can be supplied by a well without lowering the water level in the well below the pump intake.

Aquifer Yield can be defined as the maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in the hydraulic head in the aquifer.

The aquifer yield is largely of concern to the regulating authority who, aside from wanting to protect the water quality, are concerned with protecting the collective rights of all existing users in the area.

When groundwater is pumped from a well the water level begins to drop causing what is known as drawdown and a cone of depression, see Figure 10. Furthermore, with multiple wells there is a need to consider the compound drawdown, i.e. the combined impacts of groundwater abstraction, see Figure 11 .

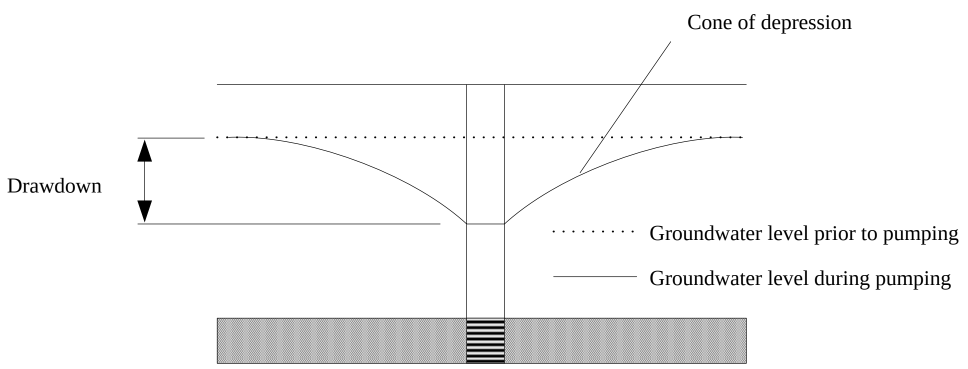

Figure 10 Well Drawdown

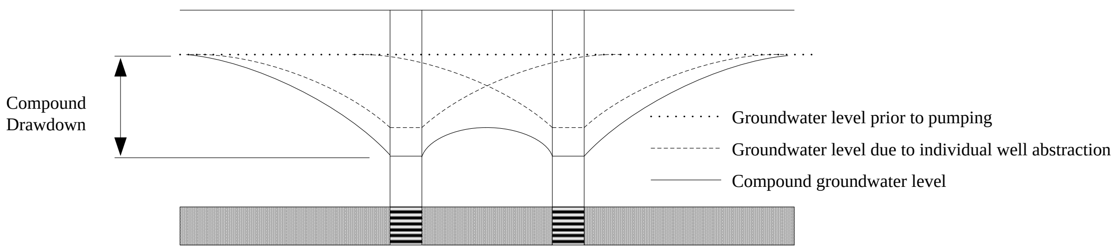

Figure 11 Compound Drawdown

To understand the radius of the drawdown from a single well, Theis [15] provided a solution which is similarly time dependent and relate the key aquifer parameters (Freeze and Cherry, 1979). This can be modified to consider the compound drawdown.

Theis Equation:

$$s = \frac{Q}{4\pi T} W(u) \qquad [\,15\,]$$

$$u = \frac{r^2 S}{4Tt}$$

s = Drawdown (m)

u= Dimensionless time parameter

W(u) Well function

Q= Pumping rate (m3/s)

r= Radius to observation point (m)

t= Length of pumping time (s)

On discharge back to the aquifer the drawdown effect is reversed whereby the water table height will increase. Hence, there is then a requirement to analyse the maximum height to prevent the occurrence of flooding either above ground (Banks, 2008) or within surrounding underground structures. Discharge is also possible to local surface water bodies and/or the sewer system. On considering discharge back to an aquifer the Theis equation remains valid although the abstraction rate term is now negative.

In summary, if a number of wells are proposed at a site an assessment must be made of the minimum distance between wells to maximise the economic abstraction from the aquifer, and if necessary discharge back to the aquifer.

Once an understanding of the well yield has been established, a further consideration is the hydraulic gradient. This is of particular interest when considering heat transport through the ground and the application of an aquifer thermal energy storage (ATES).

Thermal energy is stored both in the ground water and aquifer material and hence the volumetric heat capacity is a function of the porosity and the thermal properties of the respective fluid and solid material (Schaetzle et al., 1980) . Further background, derivation of velocity and time dependent formulae and validation is provided in Schaetzle (1980) and Dickinson (2008). Due to the complex dynamics of heat and coolth rejection into the aquifer throughout a year, the consideration eventually requires simulation using an appropriate software package such as FEFlow or HST3D-WIN.

In the UK the available groundwater at a site can be initially estimated by using a mixture of desktop resources such as borehole and well logs obtained from the BGS[5], local memoirs, maps and reports, for example, issued by IGS (1977), BGS (1987) and Allan et al (1997). These desktop resources provide data to estimate the yield either indirectly by using formulae that associate the key parameters or by providing empirical evidence of actual yields obtained in the vicinity of the site or from the aquifer type.

An initial calculation on the volumetric well yield can be made using Logan's approximation, [16] (Banks, 2008):

$$\dot{V} = \frac{Ts}{1.22} \qquad [\,16\,]$$

$\dot{V}$ Volumetric wells yield (m^3/s)

T Transmissivity (m^2/s)

s Drawdown (m)

This can be adjusted to account for possible well losses due to turbulent flow and resultant hydraulic resistance caused, for example by the well screen, see [17] (Misstear et al., 2006).

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[5] BGS - British Geological Survey

$$\dot{V} = \frac{Ts_w}{2} \qquad [\,17\,]$$

This is commonly used to make an initial assessment but should be replaced during detailed design using more detailed information about the aquifer and preferred well design.

Further to desktop calculations it is possible to also carry out laboratory tests using samples from a borehole located on site or piezometric tests based on very short almost instantaneous introductions or abstractions of water into a borehole (Freeze and Cherry, 1979). The next level of assessment is a pumping test. There is an inevitable natural path of assessment in correlation to cost; desktop studies being the least cost through to a full scale pumping test being the most expensive.

2.10 Summary of Literature Review

HT-UTES is not currently a widely used and commercially developed approach for thermal energy storage. However, although there are no examples of the scale of HT-UTES potentially considered for this study there are many examples of smaller scale HT-UTES that can be referenced. The design methodology and operational problems are reasonably well understood at this scale.

The significant issues that need to be addressed at the design stage are as follows:

- Geological/ Hydrogeological suitability for either BTES or ATES systems
- Ground system configuration
- Water Treatment
- Regulatory controls
- Accuracy of heat injection/ abstraction cycles
- Operational strategy

3 Assessment of Geological Formations for Heat Storage

3.1 Geology in the UK – An Overview

The land area of the UK is 245,966km^2 with only 1,426km^2 designated as open water (BGS, 2008b). Toghill (2000) has stated that "... the geology of Britain is immensely varied, with rocks and structures representing over 2000 million years of earth history".

The geology in the UK is generally made up of a layer of superficial deposits such as clay or sand underlain by bedrock. The superficial deposits are usually under 10m in depth, although this may be exceeded on a local scale, and are also absent in many places throughout the UK (Jackson, 2004b). Figure 12 shows a generalised surface geological map for the UK. There are a variety of surface classifications with superficial deposits, such as sand and gravel and pebbly-silty-clay dominating. Below the superficial deposits and in some cases outcroping to the surface is bedrock, shown by the coloured legend in Figure 12.

There are differences between superficial deposits and rocks and their respective sub-sets and it is useful to establish a basic definition at this juncture. Rock is a stronger material whereas soil in its simplest definition can be described "…as a sediment which has not become rock-like, or a granular residue from rock that has completely weathered (called a residual soil)" (Blyth and de Freitas, 1984). Waltham (1994) also suggests that when the uniaxial compressive strength (UCS) of a rock is less than 1MPa the material effectively becomes a superficial deposit.

Rocks and soils are mixtures of minerals so naturally, as the composition varies, so can the respective thermal properties. Also, higher porosities and the existence of fractures or fissures, and cavities can greatly affect the thermal attributes of the volume. Groundwater in the UK is present almost everywhere, but whether it is suitable for extraction for drinking water or indeed for an open loop ground energy system requires detailed hydrogeological analysis and site investigation.

Due to the variable geology in the UK the potential and performance of different ground energy systems could also vary. As has been shown in the literature review the thermal properties of geomaterials will primarily affect closed loop systems whilst the potential to abstract and discharge groundwater will lead the applicability of open loop ground energy systems.

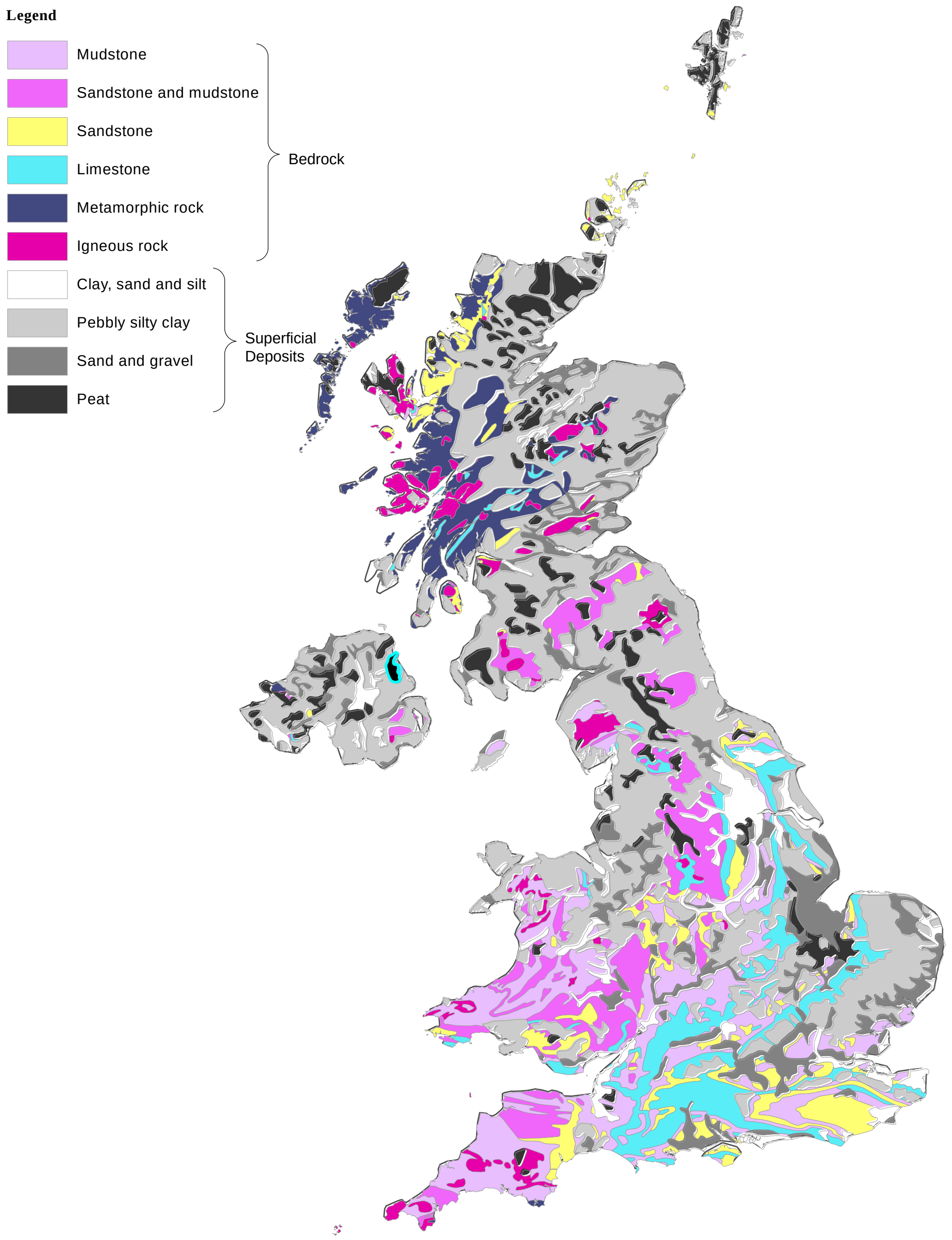

Figure 12 Map of surface geology throughout the UK (Jackson, 2004b)

3.1.1 Heat Flux in the UK

From Figure 13 it can be seen the heat flux varies throughout the country. Particularly high values are present in the south west but elevated values are also shown in the north east.

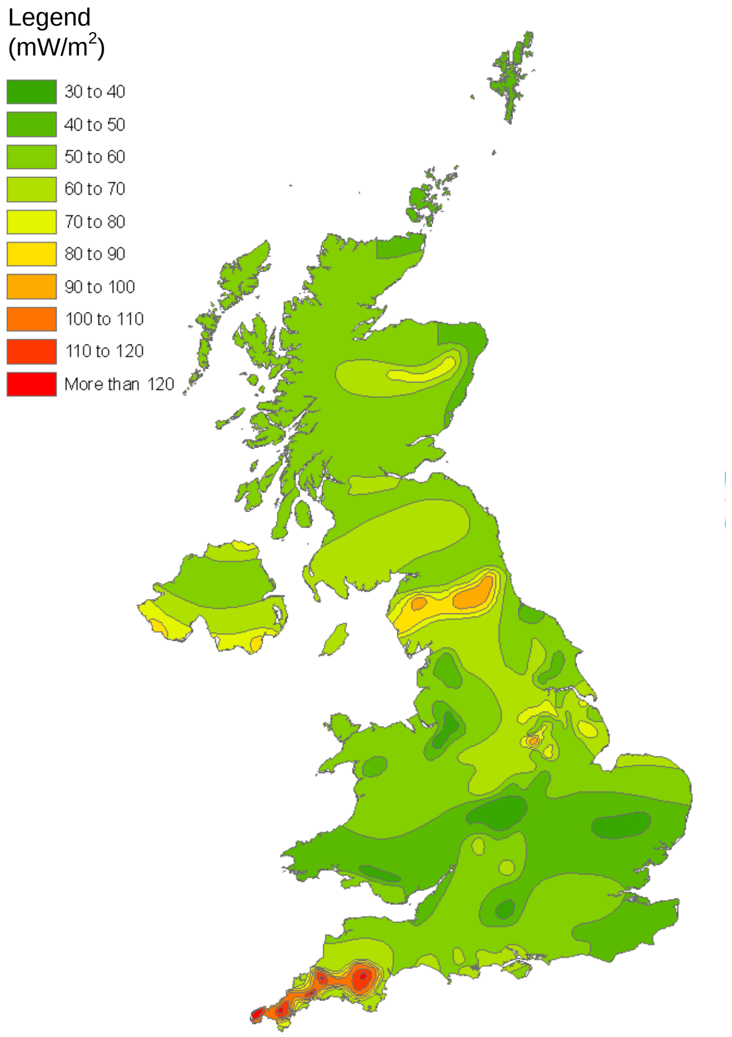

Figure 13 Map of underground heat flux throughout the UK (Jackson, 2004b)

Added to the range in thermal conductivity indicated in Figure 4 and Figure 5, it can be deduced that the thermal gradient will also vary from location to location. Whieldon and Rollin reported in Downing and Gray (1986) that this could range from 0.015 to 0.04K per m in the UK although it is unclear how this assessment has been made.

The undisturbed temperature $T_{(t=0)}$ can be calculated using the following:

$$T_{t=0} = T_m + \frac{d\theta}{dx} x \qquad \text{(Banks, 2008)}$$

3.1.2 Superficial Deposits and Bedrock Geology

In Figure 14 the superficial deposits are shown to be less than 10m in thickness throughout the majority of Great Britain, no data is given for Northern Ireland. The underlying bedrock, see Figure 15, then becomes the predominant geomaterial to consider for a vertical borehole. The dominant bedrock in England and Wales is sedimentary rock, which is made up of mudstones, sandstones and limestones. Igneous and Metamorphic rock are dominant in Scotland and Northern Ireland.

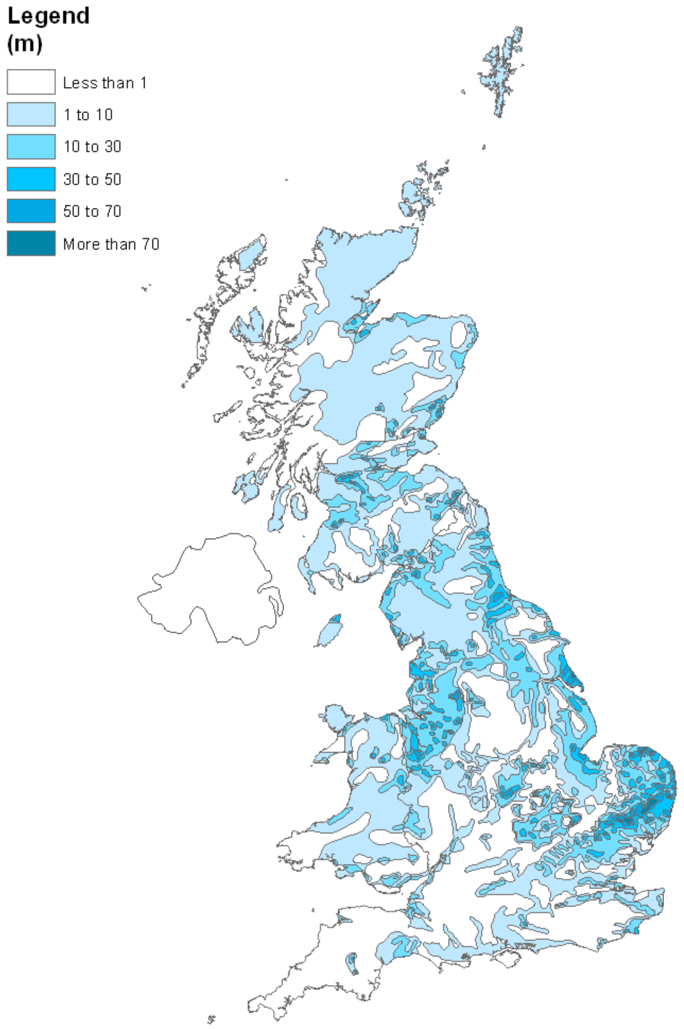

Figure 14 Map of superficial deposit thickness throughout the UK (Jackson, 2004b)

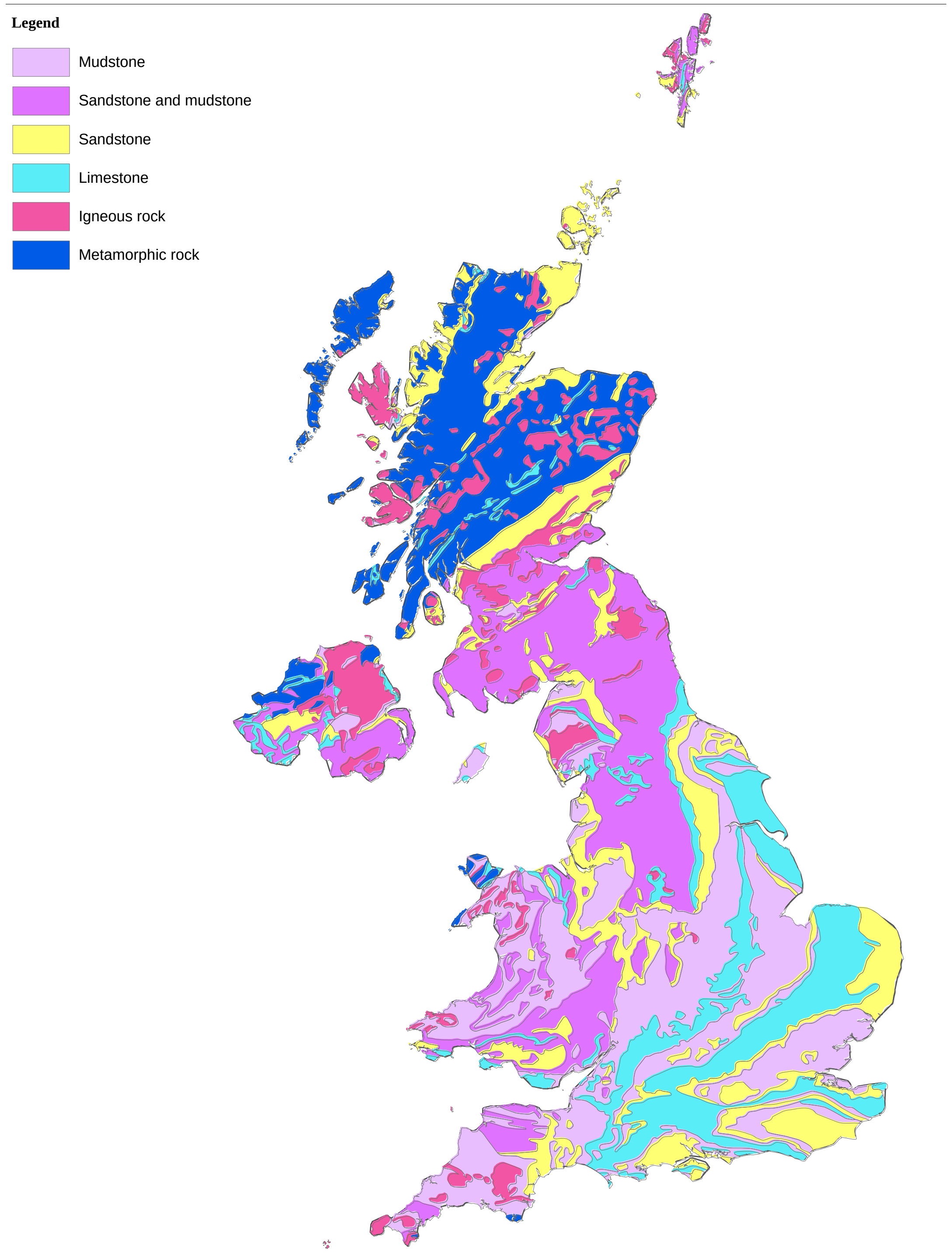

Figure 15 Map of main bedrock types throughout the UK (Jackson, 2004b)

3.1.3 UK Hydrogeology and Regulation

Figure 16 shows an overview of potential aquifer productivity throughout the UK. This map formulated by a review of over 105,000 water wells and local bedrock attempts to distinguish between different types of rock so an initial estimate can be made of a local area (Jackson, 2004b). Even without further calculation it is clear that the UK has limited potential for open loop systems by virtue of the available groundwater resource. Some regions therefore have very little or no scope for the application of open loop systems.

Definitions of the classifications used by the BGS were provided through personal communication with Andrew McKenzie at the BGS (2007).

Productive: Boreholes may yield over 20l/s
Moderate: Boreholes may yield over 5 l/s
Limited: Boreholes likely to yield over 0.5 l/s
Unproductive: Boreholes likely to yield less than 0.5 l/*s*

The map is generalised and the yields achieved will inevitably show some internal variability, nonetheless, it is unlikely that those areas identified as having limited or local yields could support a significant open loop system for an ATES system. Even those areas with moderate or productive potential may prove uneconomic or indeed, site spatial limitations might prevent significant storage potential. What has also been intimated by initially reviewing publications by the IGS (1977), BGS (1987) and Allen (1997) is that the heterogeneity of fissure flow aquifers in the UK may exhibit huge ranges in yield and storage potential dependent on well connection with major fractures in the strata.

In the UK there is a requirement prior to applying for an abstraction licence that a pump test is completed, which can be an expensive investigatory technique. Additionally, satisfactory simulation of the heat transport using an appropriate software package is also needed. There is the potential thereby to undertake a desktop survey to understand the site's hydrogeology to first assess the potential prior to triggering a full site investigation and simulation.

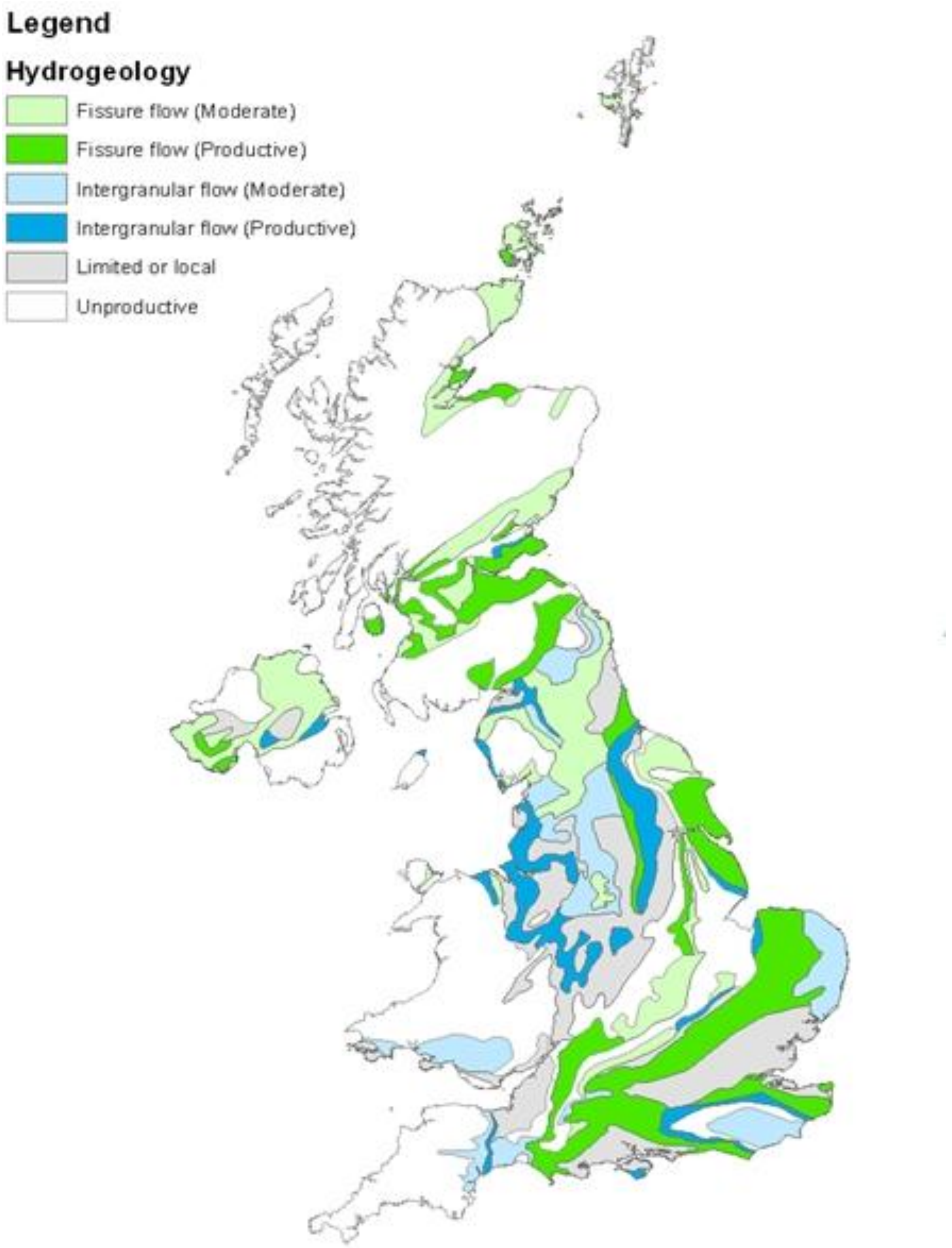

Figure 16 Aquifer Productivity in the UK (Jackson, 2004b)

The abstraction of groundwater in the UK is governed by the Water Resources Act 1991. The aquifers of the UK are monitored and regulated closely by the respective agencies for England and Wales[6], Scotland[7] and Northern Ireland[8] to ensure that they are not unduly overused or contaminated. For quantities over 20m^3/day in England and Wales an abstraction licence is required which will consider the site specific circumstances including the presence of existing licence holders in the vicinity (EA, 2005; 2007). If the intention is to discharge to a natural water body, e.g. the same aquifer as abstracted from or a surface water body, then a discharge consent from the EA is also needed. This is because the heated or cooled groundwater is considered a thermal effluent. Further discussion of the regulatory regime is presented in section 10.

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[6] England and Wales groundwater protection and regulation – Environment Agency (EA)

[7] Scotland groundwater protection and regulation – Scottish Environment Protection Agency (SEPA)

[8] Northern Ireland groundwater protection and regulation – Northern Ireland Environment Agency (NIEA)

3.2 Conceptual Models for Ground Systems

Prior to reviewing the UK potential for heat storage in more detail a number of conceptual models are presented for both BTES and ATES systems. The purpose of which is to indentify the key parameters in the ground and potential storage configurations.

3.2.1 Closed Loop HT-BTES

Figure 17 shows the baseline configuration for a BTES system. The use of a large scale storage system close to the heat source is shown in addition to smaller heat storage systems near demand. The preference of remote heat storage is led by the potential spatial constraints in urbanised areas.

The borehole array will be constructed in a compact layout to minimise the surface area: volume ratio. Due to the inherent losses through the overlaying surface this area should also be kept to a minimum and if possible, thermally insulated. Generally a cylindrical or hexagonal configuration is preferred where the overall diameter is smaller than the depth of the boreholes. The preferred spacing of the boreholes will be determined by the time between heat injection and abstraction, thermal properties of the ground and the heat injection time.

The loading and unloading configuration is likely to be as follows:

- Heat Injection; heat will initially be injected into central boreholes. As the return temperature from the borehole array increases the flow will be directed to boreholes further away from the centre.
- Heat abstraction; the process will then be reversed with heat initially abstracted from the outer boreholes.

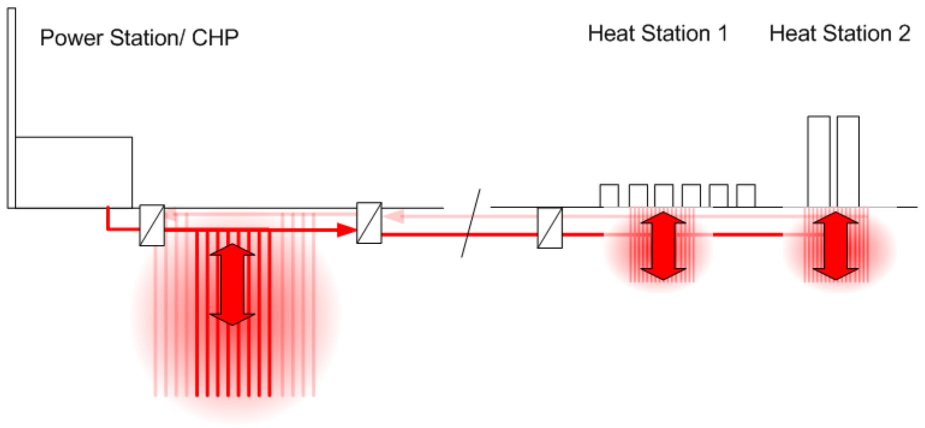

Figure 17 BTES - Closed Loop Conceptual Model

The parameters in Table 8 are those identified as important for the calculation and simulation of BTES systems.

Table 8 BTES Parameters and Methodology

Key parameters	
Geological 1. Thermal Conductivity of differing UK Bedrocks 2. Heat Flux 3. Bulk Heat Capacity 4. Potential for Groundwater Flow	Other 1. Average Annual Air Temperature 2. Borehole Thermal Resistance 3. Heat Injection Rate and Profile Heat Abstraction Rate and Profile

3.2.2 Open Loop HT – ATES

Figure 18 and Figure 19 indicate the basic loading and unloading strategy for an ATES systems. Again smaller ATES systems are shown near to the heat demand. A similar heat injection/ abstraction strategy can be used for BTES.

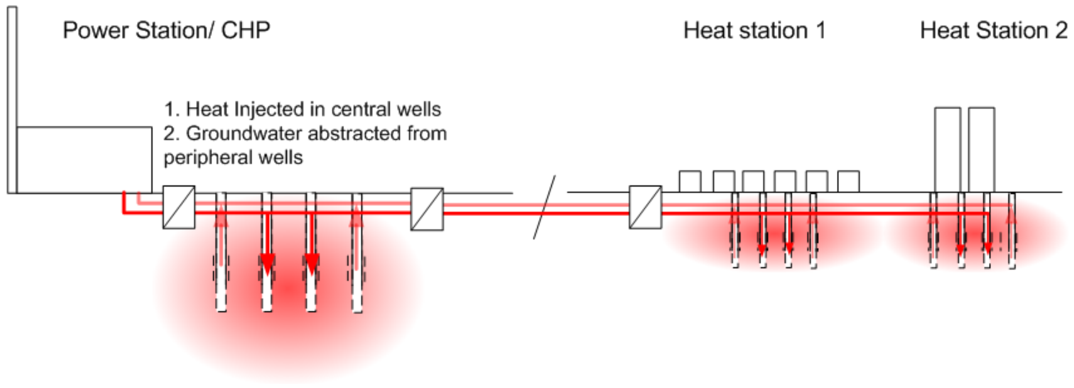

Figure 18 ATES Mode 1: Heat Rejection

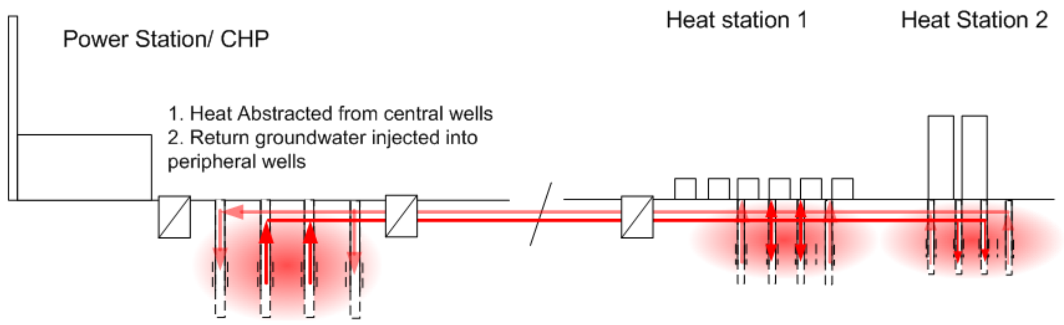

Figure 19 ATES Mode 2: Heat Abstraction

The parameters in Table **9** are those identified as important for the calculation and simulation of ATES systems.

Table 9 Phased Analysis of Open Loop HT - ATES

Parameters/ Criteria identified in Phase	
1. Transmissivity, Mean/ Inter-quartile range (from EA/ BGS literature) 2. Porosity (from EA/ BGS literature) 3. Bulk Heat Capacity (interpreted from VDI, EA and BGS data) 4. Hydraulic Conductivity 5. Aquifer Depth	1. Heat/ Temperature Supply Profile 2. Heat/ Temperature Demand Profile 3. Well Configuration and Spacing

3.3 Basic Heat Storage Model

The initial steady storage model is shown in Figure 20. This uses Kopp's Law as the basis for calculating the maximum theoretical storage possible in a volume of geomaterial. The vertical loss through the upper and lower confining areas are also shown. These losses along with lateral losses due to groundwater flow are considered in chapter 5.

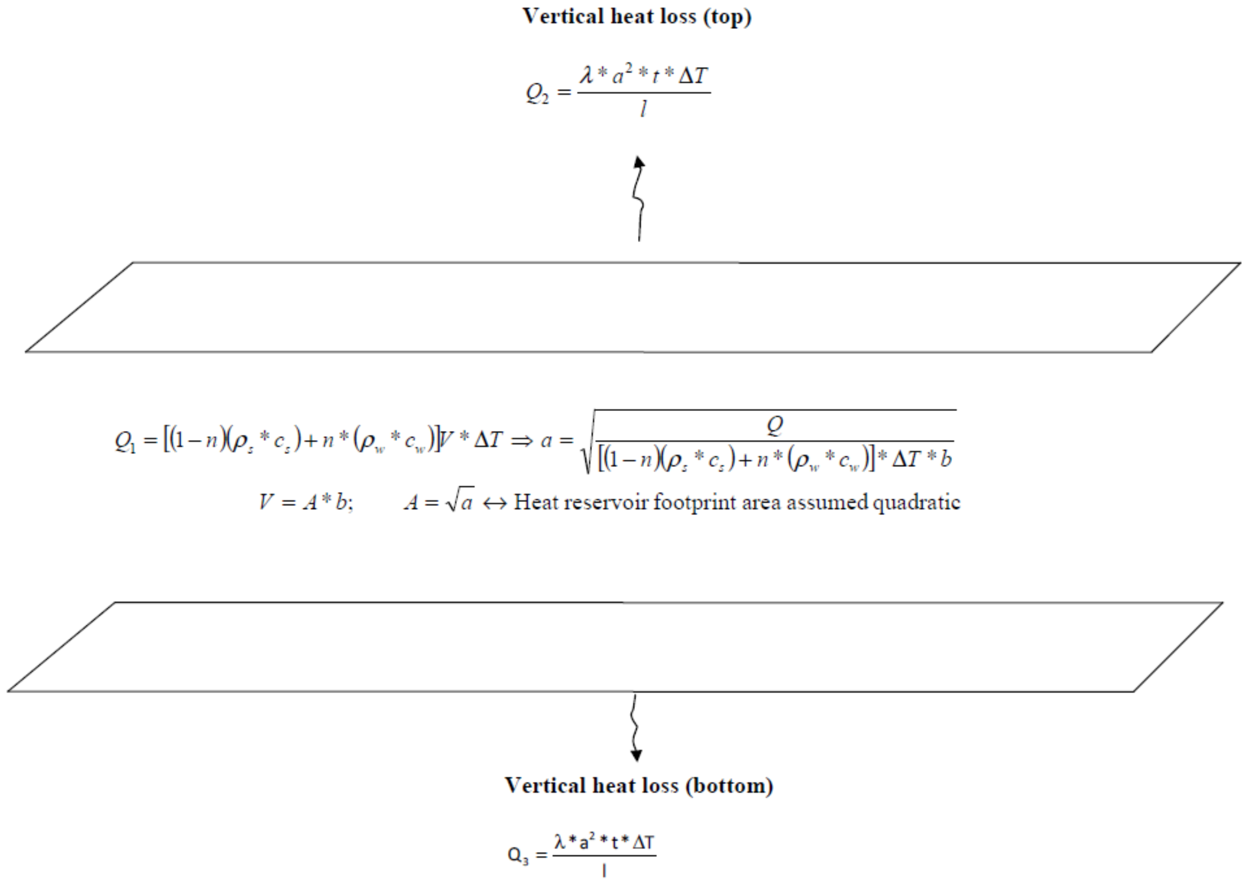

Figure 20 Heat Storage Model

Where:

ΔT:	Injection – aquifer temperature difference
b:	Aquifer thickness
n:	Porosity
ρ_s:	Density (solid phase)
c_s:	specific heat capacity (solid phase)
ρ_w:	Density (water)
c_w:	Specific heat capacity water
a:	Footprint of heat reservoir side length
Q_1:	Heat energy
Q_2:	Rate of heat loss through upper confining layer
Q_3:	Rate of heat loss through lower confining layer
t:	Time period
λ:	Thermal conductivity

3.3.1 Volumetric Analysis

Figure 21 to Figure 26 provide an indication of the theoretical volume of bedrock required to store heat and the radial sphere of influence for each temperature regime. The depth of bedrock used in these examples is 100m.

An example heat storage period of 3 months per year is used. Heat injection is assumed as steady state over the period at the rate noted on the x-axis. Kopp's Law provides idealistic and optimistic heat storage potential but this initial step enables the scale to be understood in basic terms.

The main factors which will reduce or limit this potential are briefly outlined as follows:

BTES

Limiting factors; Heat transfer rate possible through closed loop pipework into bedrock

Reducing factors; groundwater flow causing lateral heat loss, conductivity of above and below geology, return temperature from district heating network, maintenance requirements and spatial limitations.

ATES

Limiting factors; Regulatory constraints – impact on other groundwater users, groundwater abstraction/ injection rates possible.

Reducing factors; groundwater flow, heat loss to above and below geology, return temperature from district heating network, maintenance requirements

Temperature Regime - 35°

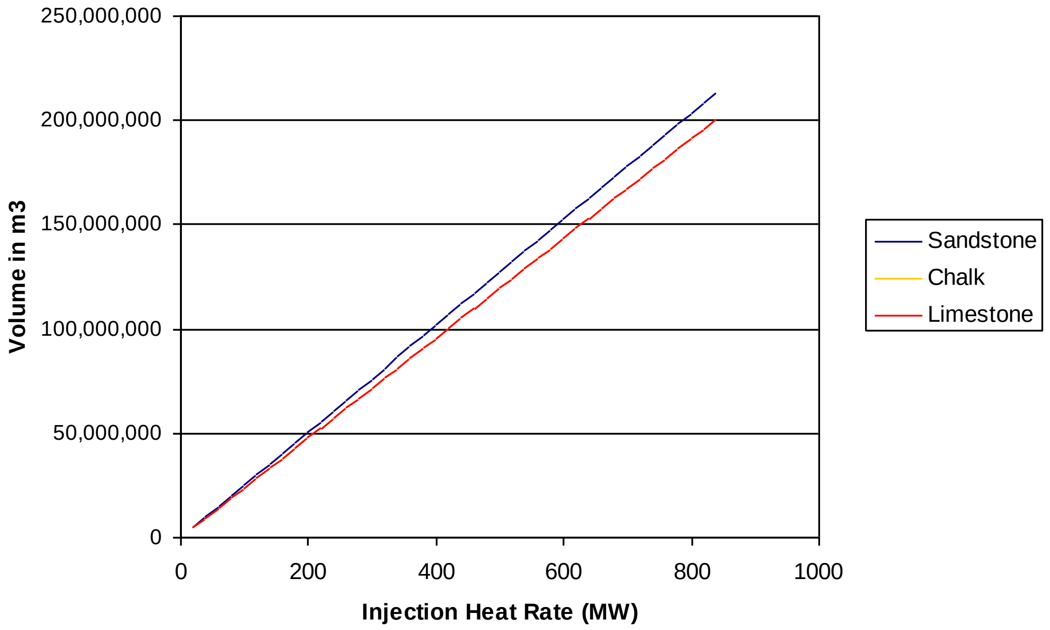

Figure 21 35°C Volumetric Analysis (3 month injection period)

Temperature Regime - 120°

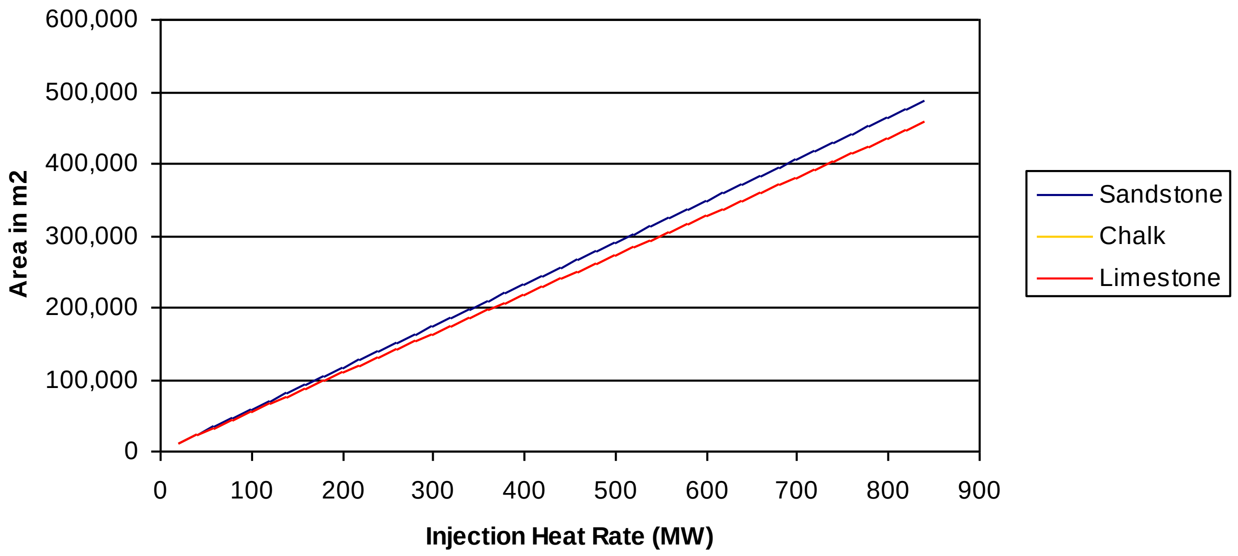

Figure 23 120°C Volumetric Analysis (3 month injection period)

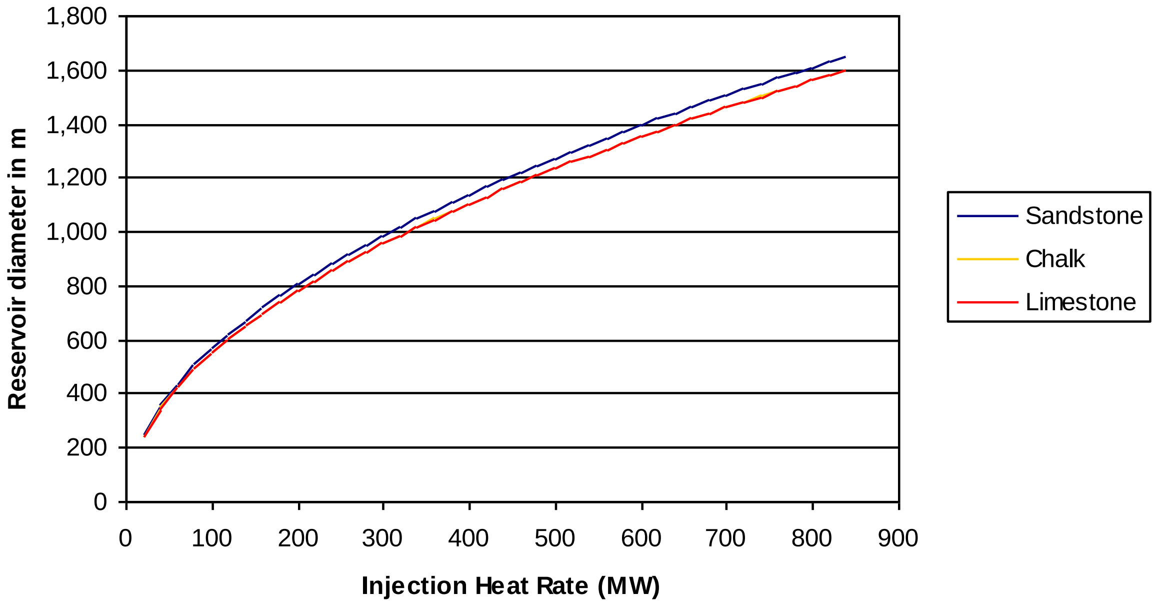

Figure 22 35°C Spatial Analysis – 100m Deep Aquifer (3 month injection period)

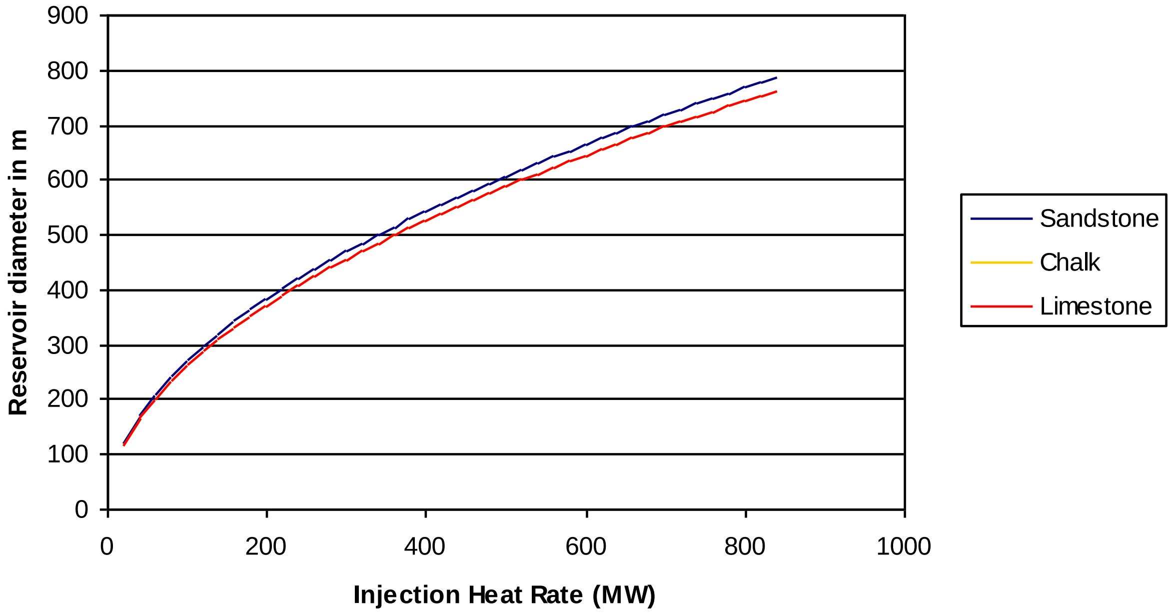

Figure 24 120°C Spatial Analysis – 100m Deep Aquifer (3 month injection period)

Temperature Regime - 200°

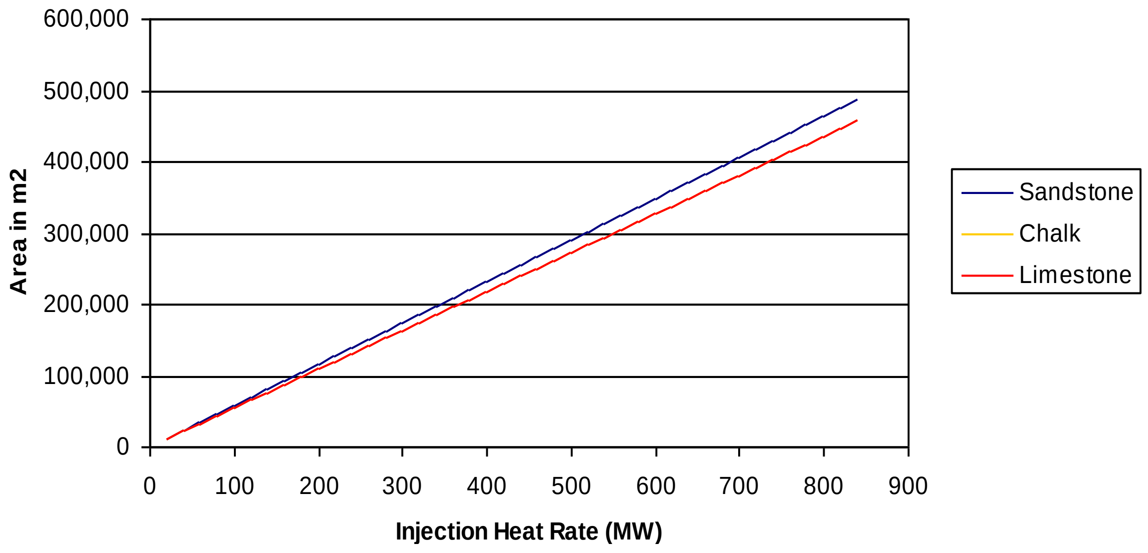

Figure 25 200°C Volumetric Analysis (3 month injection period)

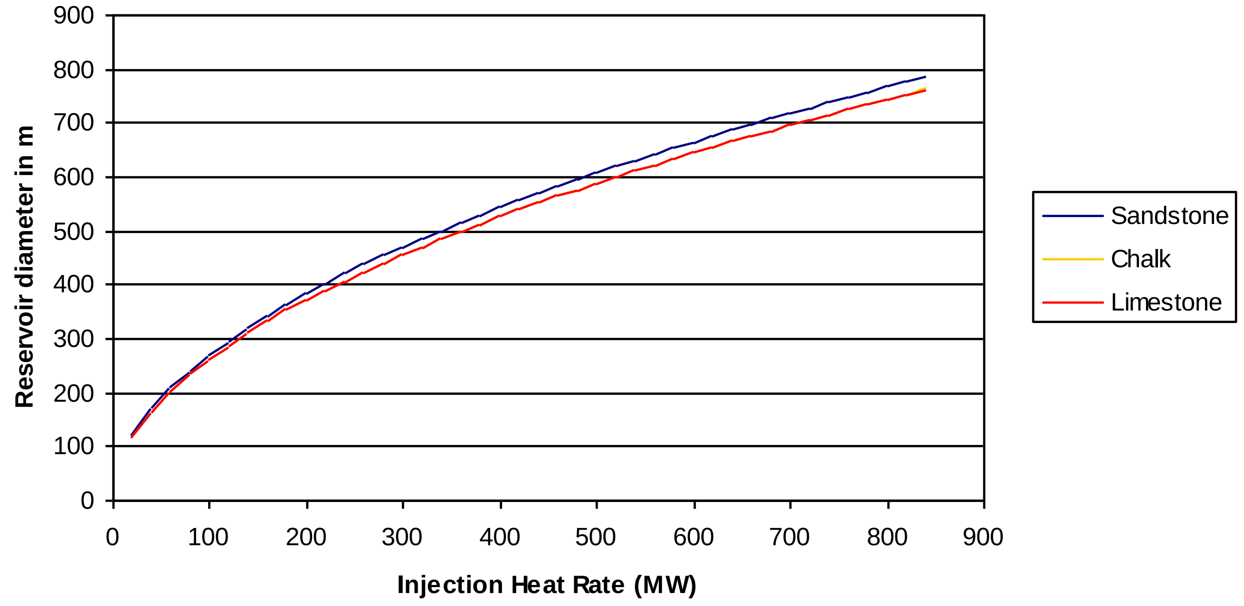

Figure 26 200°C Spatial Analysis – 100m Deep Aquifer (3 month injection period)

3.4 Ground Heat Storage in the UK

The potential for a geological unit to store heat is defined by its heat capacity. The range of heat capacity of the solid geology is relatively low and volumetric heat capacity values for main bedrocks ranges between values of 2100 and 2550kJ/m^{3}K (VDI 2000). It is therefore to a lesser extent the heat capacity but the heat transport mechanisms which determine the practical potential of storing heat in a geological unit.

Prime heat transport mechanisms are by advection in open loop systems (by a fluid, due to the fluid's bulk motion in a particular direction) or conduction in closed loop systems (the transfer of thermal energy between regions of matter due to a temperature gradient).

Mechanisms relying on the transport of heat via fluids are of higher efficiency due to the higher rates of transfer and control that can be achieved. In contrast; in the absence of a fluid, heat transfer predominantly via conductive transport and rates of transport are described by the thermal conductivity of the geological unit).

In an ATES system the advective heat transport is facilitated via the (forced, gradient, convective) flow of groundwater.

In the UK, sandstone and limestone formations form the principal groundwater reservoirs or aquifers. "An aquifer is commonly defined as a permeable geological unit that is sufficiently porous to store water and permeable enough to allow water to flow through them to supply reasonable amounts water to wells. In aquifers water flows through voids, or pore spaces. Pore space is referred to as the porosity and represents the total volume of water that the rock can store. "This may be in the minute spaces between the grains of a sandstone, when it is referred to as intergranular porosity, or in the small cracks and fractures that are more usual in limestones and older compact rocks, which is termed fracture porosity." The pore spaces in an aquifer must be interconnected so that water can flow through the rock.

In the UK, geological formations forming most important aquifers are of Cretaceous (Chalk), Permo-Triassic (Sherwood Sandstone and Basal Permian Sands) or Jurassic (Oolitic Limestones) origin. They occur within a section of the geological sequence (referred to as the "Younger Cover", ranging in age and with formations of the Permian, generally forming the oldest and deepest water bearing strata of high porosity (see Figure 27). Formations of the "Younger Cover" are present in the English lowland areas of the south, east, and Midlands but also in the north east of Northern Ireland.

Formations of the "Younger Cover" are underlain by much harder and compact rocks of Carboniferous and Devonian 'Older Cover' origin of lower permeability. Formations of the "Younger Cover" are absent in Scotland, Wales and Cornwall where the solid geology is dominated by Carboniferous and Devonian 'Older Cover' and "impermeable basement" geology (see Figure 27).

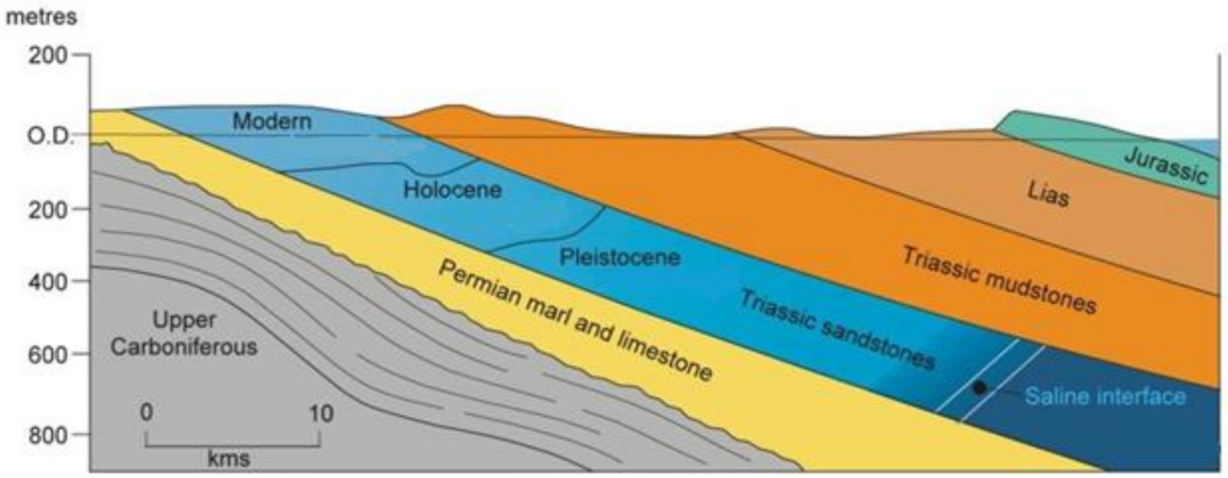

Figure 27 Typical stratification of strata of the "Younger Cover" – example based on the geology of the East Midlands

In the East Midlands and the south east of England formations of the Jurassic (Limestones) and Cretaceous (Chalk) origin are widely utilised as a source for freshwater abstraction. Where it outcrops further west the formations of the Permo-Triassic sandstones are similarly utilised.

Searching for geological formations suitable for the storage of significant quantities of heat resulted in a focus on Permo-Triassic sandstones rather than formations of Jurassic and Cretaceous origins for the following reasons:

1. Aquifers of the Jurassic and Cretaceous (Chalk) are generally at relatively shallow depths. Where prevalent at shallow depths aquifers are utilised for freshwater abstractions. Injection of high temperatures into aquifers strata utilised for freshwater abstraction is likely to be prohibitive.
2. High permeability zones within the Cretaceous are to be found in major fracture zones of the Chalk only. This zone is generally confined to the upper (<10-30m) part of the Chalk. This would result is relatively thin unit (10-30m) of the aquifer used as storage medium. The low thickness would have to be compensated by increasing the heat reservoir area resulting in high fluxes of heat losses.
3. In contrast to the above, formations of the Permo-Triassic sandstones provide relatively high permeable aquifer units of significant thickness (>100m) and at greater depths.

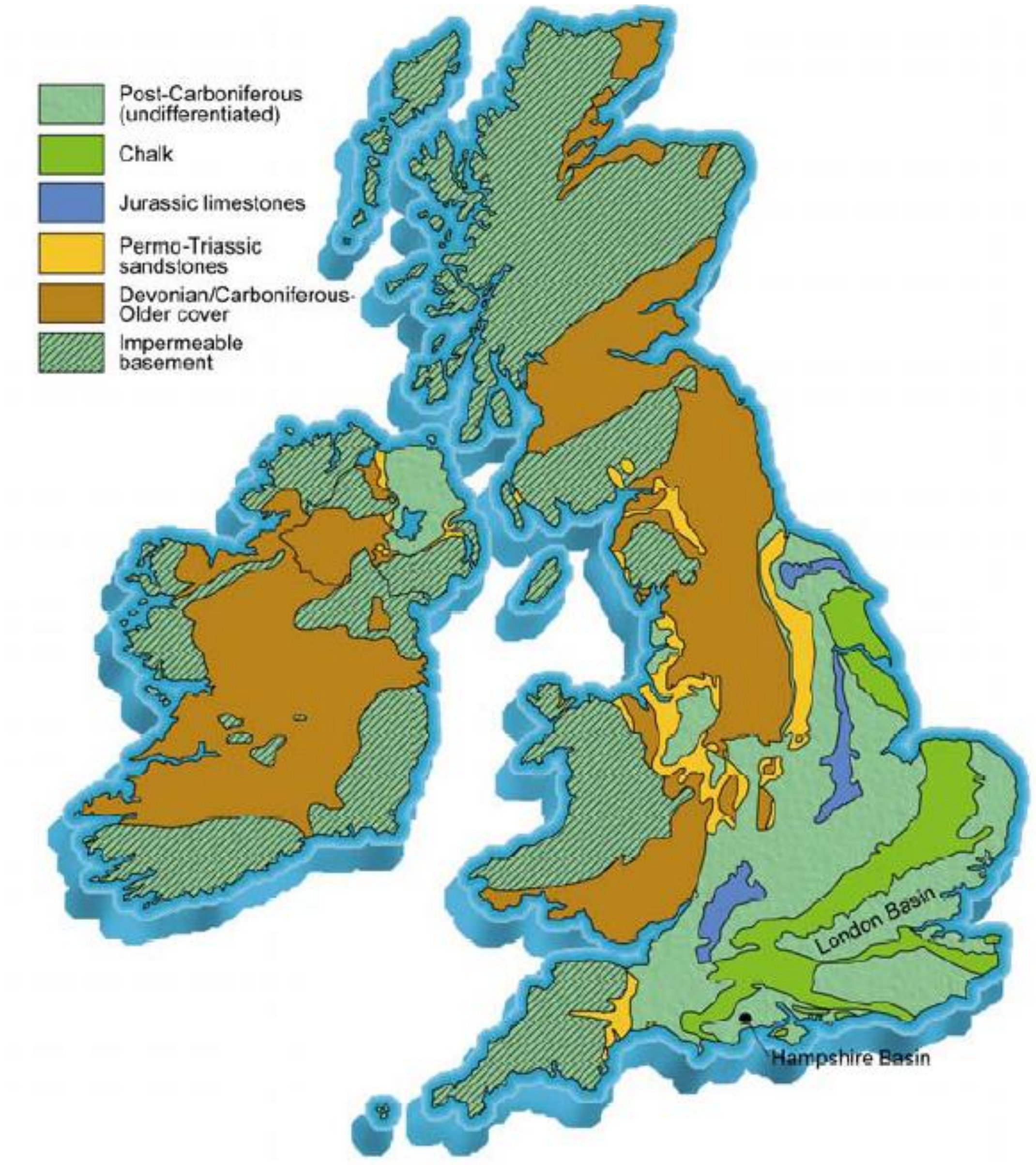

Figure 28 Distribution of principal aquifers in Britain and Ireland

3.5 System Parameter Variance for Borehole and Aquifer Storage

3.5.1 Borehole Thermal Energy Storage - Vertical Closed Loop

Geology Analysis

To analyse the predominant geology for closed loop vertical systems it is first useful to consider the surface geology throughout the UK. Figure 12 on page 18 shows the range in main geology classifications. The data set for surface geology has been analysed using ArcMap and Figure 29 shows the proportion of each classification in the UK. Superficial deposits (SD) cover ~57.5% of the UK. These include a mix of unconsolidated soils such as clays, silt and sands. Sedimentary rocks (SR), such as limestone and sandstone cover 33.3% with metamorphic (B) and igneous (B) covering just 5.5 and 3.7% of the UK respectively.

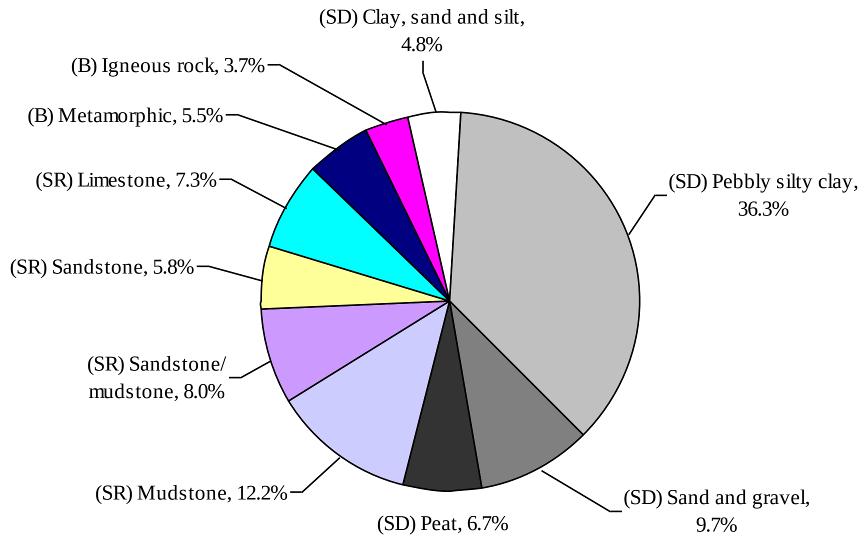

Figure 29 Surface geology by area in the UK

However, as indicated by Figure 14, the thickness of the superficial deposits varies considerably throughout the UK and hence this cannot necessarily be classified as the dominant geomaterial along the length of a vertical borehole or well.

Thickness data were not available for Northern Ireland but for the purposes of this analysis similar ratios will be assumed for this region as for the rest of Great Britain. Only in isolated areas are much thicker deposits present, for example, in East Anglia and parts of the north-west and north-east. Generally, the superficial deposits are less than 10m in thickness. This is shown more explicitly in Figure 30 which provides a breakdown of the thickness range by area for Great Britain. It can be said that for more than 80% of the UK the bedrock is either directly exposed at the surface or the superficial deposits are less than 10m thick. This percentage rises to 95.5% if superficial deposits between 10 and 30m are also considered as thin and insignificant.

This suggests that the superficial deposits are not a significant lithology to consider in a spatial analysis of vertical closed loop BTES or open loop ATES in the UK. The focus for the remainder of this section concentrates on the bedrock type.

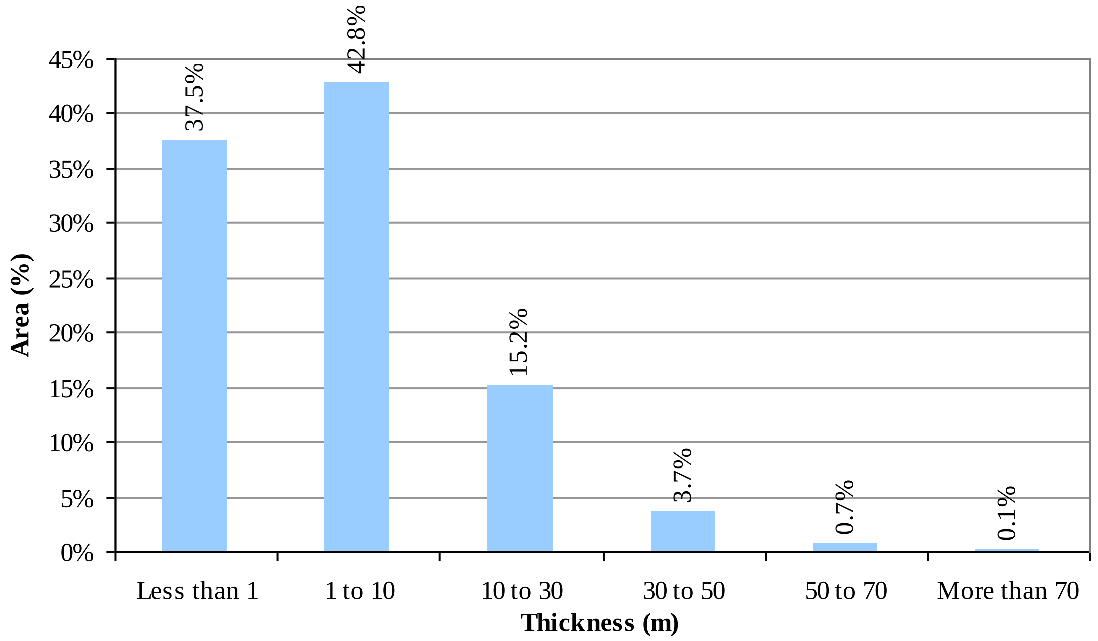

Figure 30 Range of thickness of superficial deposits in Great Britain[9]

The bedrock throughout the UK has been interpreted to establish the spatial breakdown of each of the highlighted rock types. Figure 31 shows the initial results of the analysis. Sedimentary bedrock is dominant in 76.1% of the UK, which equates to over 187,000km^2. Mudstones are the most common place at 23.6%, with a sandstone and mudstone mix[10] at 21.7%, sandstone at 16.9% and limestone at 13.9%. By comparison metamorphic rocks (14.6%) and igneous rocks (9.3%) are less common place, almost solely found in Scotland with isolated occurrences in Northern Ireland, south-west England and north-west Wales. Sedimentary rocks tend to dominate throughout England and Wales.

The breakdown of metamorphic rocks is as follows:

- Meta-Quartzite – 9.3% of total land area in UK
- Gneiss – 2.0%
- Mica-shists – 2.0%
- Other – 1.3%

The breakdown of main igneous rocks is as follows:

- Basalt – 4.6%
- Granite – 3.1%
- Rhyolite – 0.6%
- Other – 1.0%

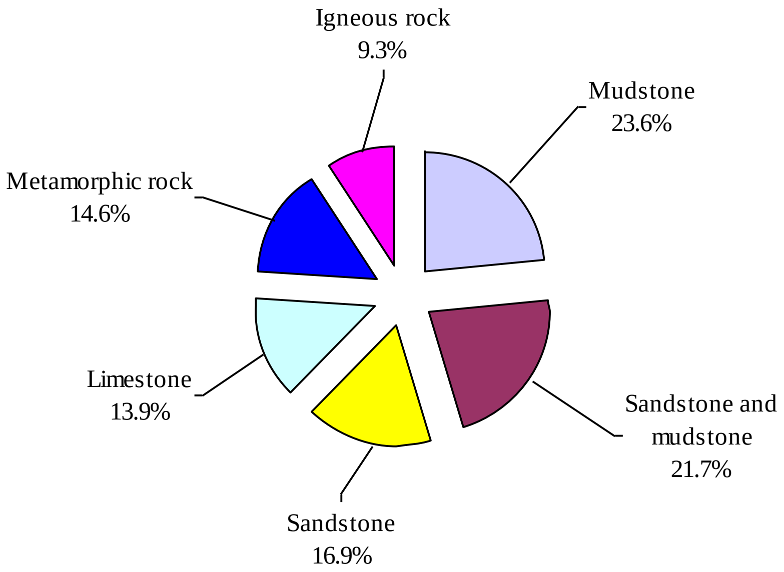

Figure 31 Spatial analysis of bedrock in the UK

Ground Thermal Properties

The referenced thermal conductivities for the dominant bedrocks in the UK are shown in Figure 4.

Using typical values, the area-averaged thermal conductivity for sedimentary rocks is 2.4W/mK. The area-averaged thermal conductivity for all bedrocks in the UK is 2.7W/mK.

The typical thermal conductivities for the superficial deposits are shown in Figure 5 on page 12 where the range for saturated[11] gravels, sands and silts is 1.7-2.4W/mK. Only where the deposits are both significantly thick (>30m) and the respective thermal conductivity is low compared to the bedrock geology will the average thermal conductivity be markedly affected. Hence, the presence of thicker superficial deposits overlying such bedrock as Granite, Gneiss, Rhyolite and Meta-quartzite could significantly influence the bulk thermal conductivity. Such bedrock types are mainly found in

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[9] Superficial deposit thickness data was not available for Northern Ireland

[10] Sandstone and Mudstone: depicts bedrock geology which is typified by layers of sandstone, and mudstone.

[11] For vertical systems both the bedrock and superficial deposits are considered to be fully saturated.

Scotland and the South West of England where the thickness of superficial deposits, if present, is generally low. Again using typical values, the presence of superficial deposits is unlikely to have such an influence with sedimentary rocks which generally have a lower thermal conductivity. For the high end of range sedimentary rocks such as sandstone the influence will be higher.

The referenced volumetric heat capacities for the dominant bedrocks in the UK are shown in Figure 6 on page 13. Again using typical values, the area averaged volumetric heat capacity for sedimentary rocks is ~2232kJ/m^3.K, and for all bedrocks, ~2235kJ/m^3.K

3.5.2 Ground Temperatures

Heat Flux

The variation in heat flux in the UK is shown in Figure 15 and in Figure 32 by area. By far the highest values, >100mW/m^2, are isolated to the granites in the south west. This only accounts for ~1% of the total land area. The average heat flow by area is 56.5mW/m^2 with over 91% of the UK having a heat flux of between 40 and 70mW/m^2. This underlines the minimal higher temperature and enthalpy geothermal resource in the UK.

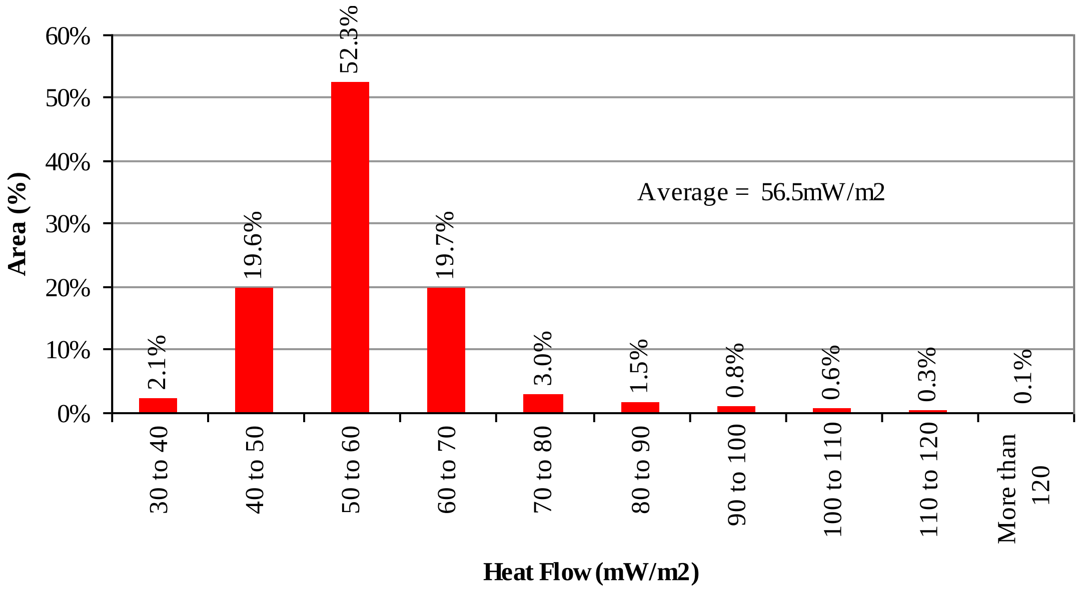

Figure 32 Heat flow by area in the UK

Thermal Gradient

The highest thermal gradient will occur where there is high heat flux but low thermal conductivity. It is not reasonable to simply match the highest heat flux with the lowest thermal conductivity to calculate the highest thermal gradient as they are not coincidental. It is clear however that the maximum gradient is very likely to occur in the south west of England due to the much higher heat flux.

As the granite, which is the focus of concentration for the highest heat flux in the south west, has a relatively high thermal conductivity (3.4W/mK), the thermal gradient can be estimated[12] to be ~3.5K/100m. Nearby basalt, marked in Figure 33, by comparison, has a typical value of 1.7W/mK. At this location the heat flux is still considered to be between 100 and 110mW/m^2 and therefore the thermal gradient could be estimated to be much higher at ~6.2K/100m.

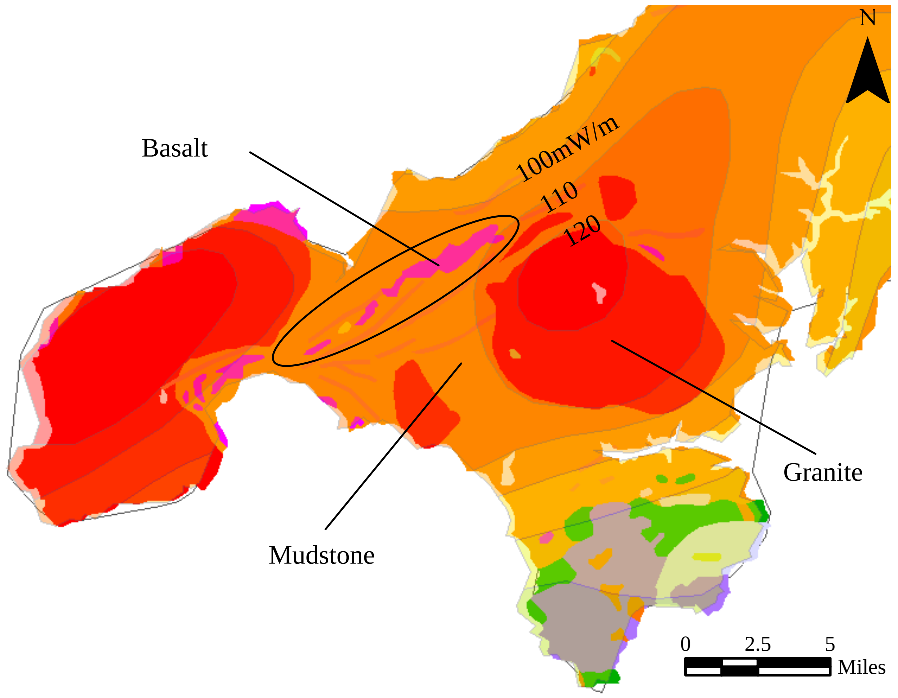

Figure 33 Region of estimated highest thermal gradient in the south west of the UK (Jackson, 2004a; BGS, 2008a)

A low heat flux and high thermal conductivity is synonymous with a relatively low thermal gradient. Again, it is not necessarily valid to match the lowest heat flux with the highest thermal conductivity to calculate the lowest thermal gradient in the UK. However, in this case it is reasonable to estimate that the lowest thermal gradient will occur with the higher conductivity metamorphic rock found in Scotland.

Taking an example location in the north east of Scotland, see Figure 34 , the heat flux is between 40 and 50 mW/m^2 and the typical value for meta-quartzite is 6W/mK. Using a mid-range value of 45mW/m^2 for the heat flux, the thermal gradient can be calculated to be 0.75K/100m.

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[12] The highest heat flux has been taken to be 120mW/m^2.

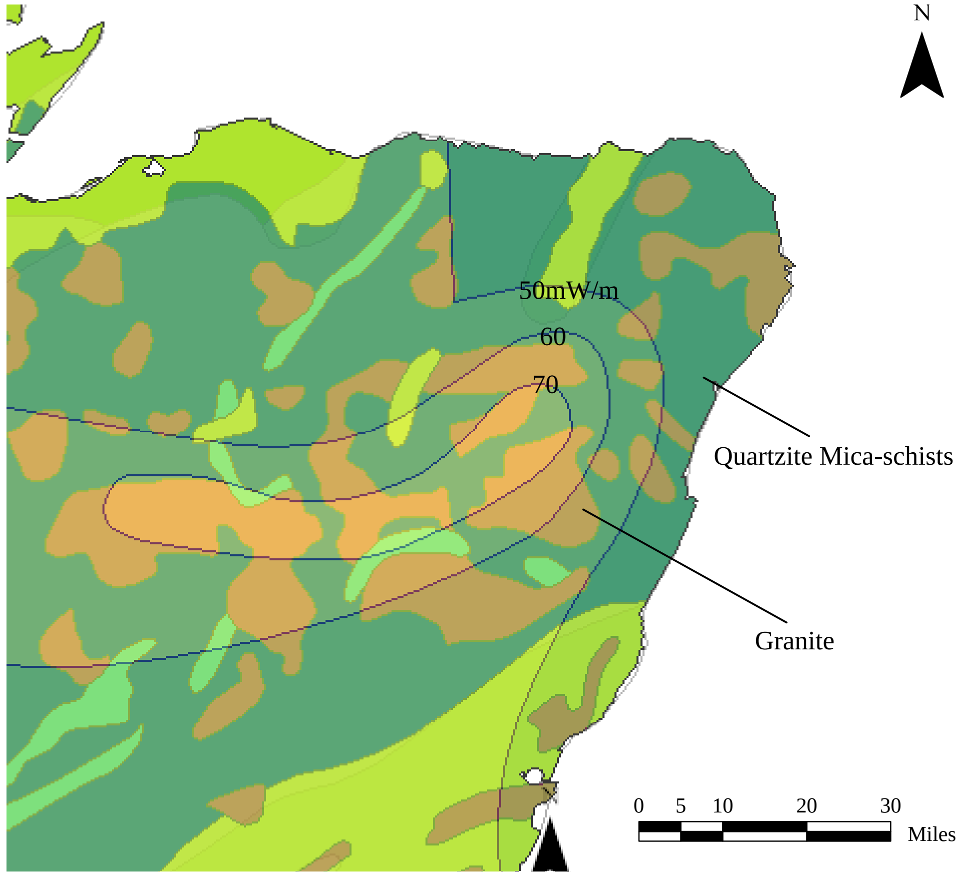

Figure 34 Location of estimated lowest thermal gradient in the north east of the UK (Jackson, 2004a; BGS, 2008a)

Therefore, the estimated range of the thermal gradient for the UK is ~0.8 to ~6.2K/100m.

The average thermal gradient for bedrocks, by considering the mean heat flux (56.5mW/m^2) and average respective thermal conductivity (2.7W/mK), can be estimated to be 0.021K/m or 2.1K/100m.

Mean Borehole Temperature in the UK

Using the referenced data for thermal conductivity, heat flux and temperature throughout the UK it is now possible to understand the range in mean temperature for a nominal 100m borehole for a vertical GLHE installation. The highest borehole temperature will occur with the highest combination of the mean air temperature and thermal gradient. Conversely, the lowest mean borehole temperature will occur with the lowest permutation.

By referencing Table 7, the average UK temperature for the 5 years from 2003 to 2007 years is 9.6˚C. The lowest average temperature is 7.9˚C in North Scotland, and the highest is 10.9 in South East and South England.

It is coincidental that the lowest estimated thermal gradient is likely to be North Scotland which also experiences the lowest mean air temperatures. Using the example location identified in Figure 34 the lowest mean borehole temperature $(\overline{T}_{bl})$ is estimated as follows:

$$\overline{T}_{bl} = 7.9 + \frac{0.0075\text{x}100}{2} = 8.3°\text{C}$$

In comparison the highest mean air temperature in East Anglia and South and South East England does not coincide with the highest thermal gradient. However, the south west of England still experiences a relatively high mean air temperature of 10.4°C. The highest mean borehole temperature $(\overline{T}_{bh})$ is estimated as follows:

$$\overline{T}_{bh} = 10.4 + \frac{0.062\text{x}100}{2} = 13.5°\text{C}$$

A mean borehole temperature for UK bedrock $(\overline{T}_{b})$ can be estimated using the respective average thermal conductivity, mean air temperature and heat flux:

$$\overline{T}_{b} = 9.6 + \frac{0.021\text{x}100}{2} = 10.7°\text{C}$$

3.5.3 Aquifer Thermal Energy Storage

The section presents the results from the hydrogeology spatial review.

Hydrogeology Analysis in Shallow Aquifers

Figure 35 shows the limited area in the UK which can be exploited for ground water abstraction. The dataset was analysed using ARCGIS. Only 19.7% of UK bedrock is classified as productive whilst a further 20.3% is classified as having only moderate yields. The remaining 60% of the UK is classified as unproductive or having limited or only local potential. This has an immediate impact of reducing the potential to install an ATES system in the UK.

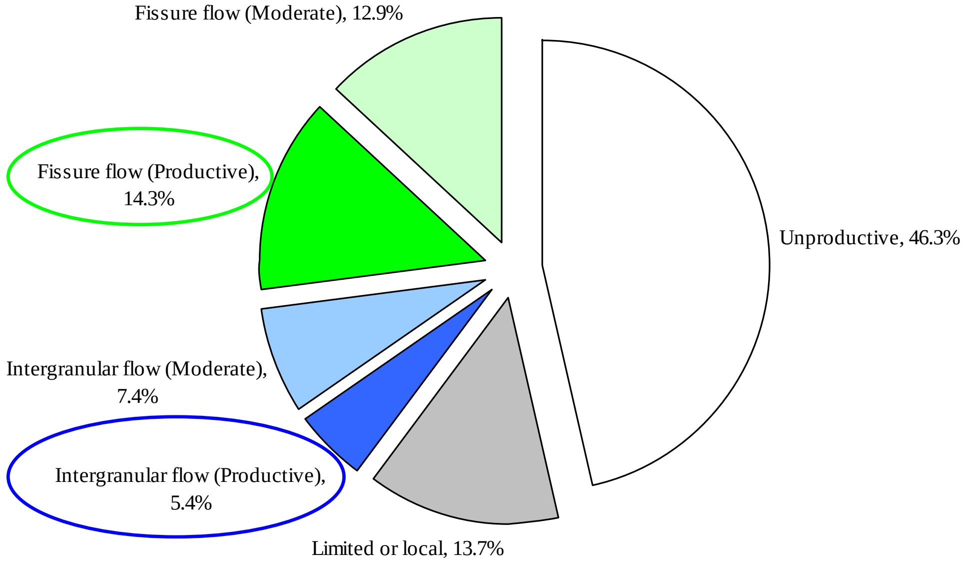

Figure 35 Hydrogeology of the UK by area

The groundwater resource was then broken down by aquifer type and region with associated references for aquifer properties. This is summarised in Figure 36.

Five productive aquifers are indentified in England and Wales; the Chalk (1), the Jurassic Limestones (2), the Magnesian Limestones (3), the Lower Greensand (4) and the Permo-Triassic Sandstones (5). Where necessary each aquifer is further broken down by region. The two dominant aquifers are the Chalk and the Permo-Triassic Sandstones. The five aquifers are mainly concentrated within England, with the only notable productive aquifer outside this boundary being in North Wales, the Vale of Clywd (5E).

In Scotland, there are 2 main aquifer types, the Carboniferous and Old Red Sandstone. In southern Scotland these two aquifers are sporadically mixed (6), with a smaller concentration of sandstone where the groundwater flow is predominantly intergrannular (8). Aside, a small area of Old Red Sandstone around Inverness (7) the vast majority of Scotland is underlain by impermeable rock with limited or no potential for abstraction.

In Northern Ireland, there are again two main aquifers, the Permo-Triassic Sandstones to the east and the Carboniferous Limestones to the west.

Further potential for aquifer storage is also possible in deeper sandstone aquifers which are shown in Figure 37. Due to the limited information on the properties of these aquifers only limited desktop interpretation is possible.

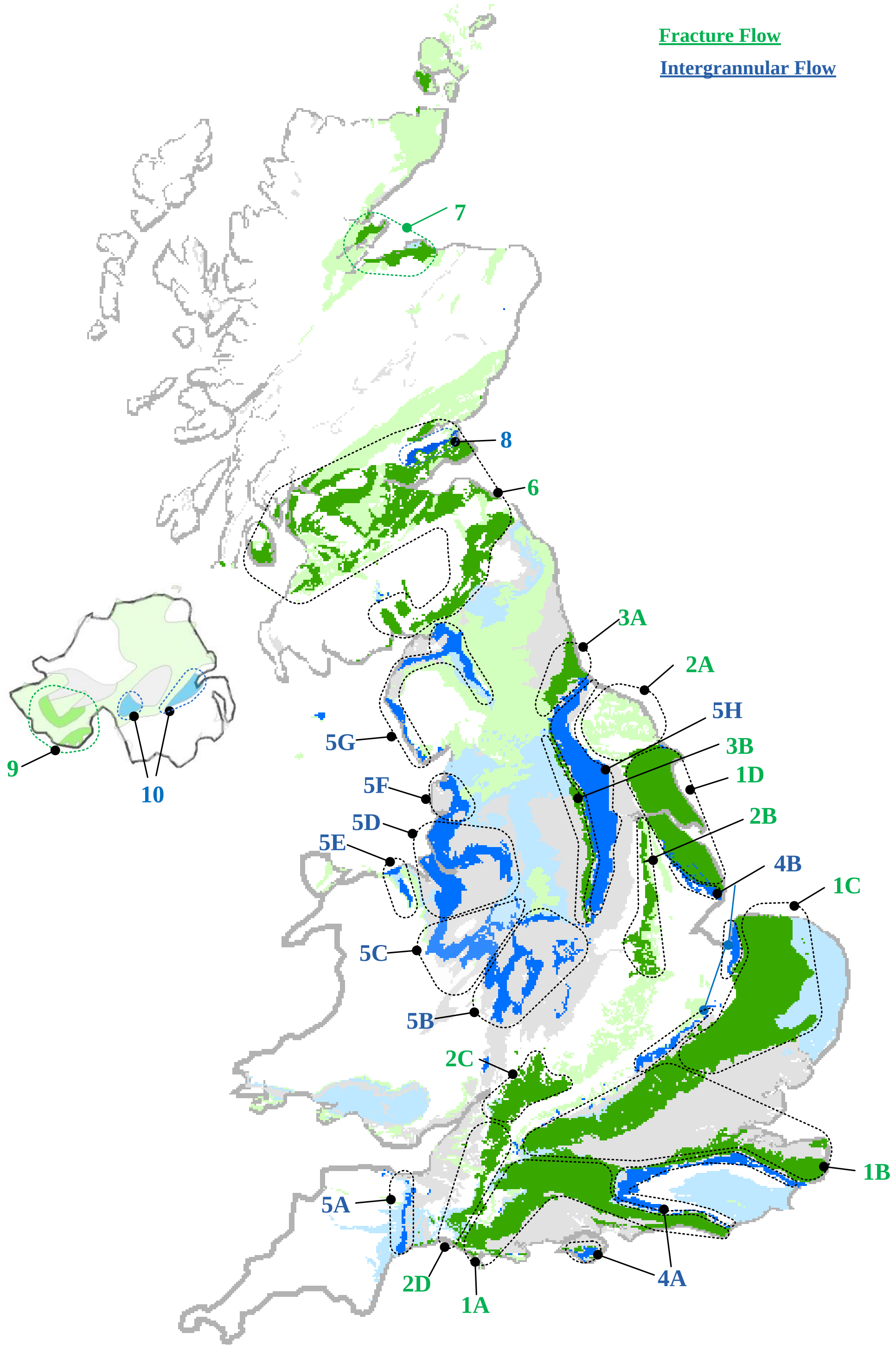

Figure 36 Identification map of productive aquifers and Region

Table 10 Aquifer Properties Reference

Aquifer Code	Aquifer Type	Region Code	Region	
1	Chalk	A	South of England	Allan et al (1997)
		B	Thames Basin	Allan et al (1997)
		C	East Anglia	Allan et al (1997)
		D	Yorkshire Humberside and Lincolshire	Allan et al (1997)
2	Jurassic Limestones	A	County Durham	Allan et al (1997)
		B	East Midlands	Allan et al (1997)
		C	Cotswolds	Allan et al (1997)
		D	Bristol Channel	Allan et al (1997)
3	Magnesian Limestone	A	Durham	Allan et al (1997)
		B	Yorkshire and Nottinghamshire	Allan et al (1997)
4	The Lower Green Sand	A	The Weald and IofW	Allan et al (1997)
		B	Bedford and Cambridge	Allan et al (1997)
5	Permo-Triassic Sandstones	A	South West	Allan et al (1997)
		B	West Midlands	Allan et al (1997)
		C	Shropshire	Allan et al (1997)
		D	Cheshire and S. Lancs	Allan et al (1997)
		E	Fylde	Allan et al (1997)
		F	Vale of Clwyd	Allan et al (1997)
		G	North West	Allan et al (1997)
		H	North East	Allan et al (1997)
6	Mix of Carboniferous and Upper Old Sandstone		Scotland	BGS (1998), MacDonald et al (1997)
7	Upper old red sandstone		Scotland	BGS (1998), MacDonald et al (1997)
8	Upper Old Red Sandstone of Fife		Scotland	BGS (1998), MacDonald et al (1997)
9	Carboniferous Limestones		Northern Ireland	Robins (1997)
10	Permo-Triassic Sandstones		Northern Ireland	Robins (1997), Kalin (2007)

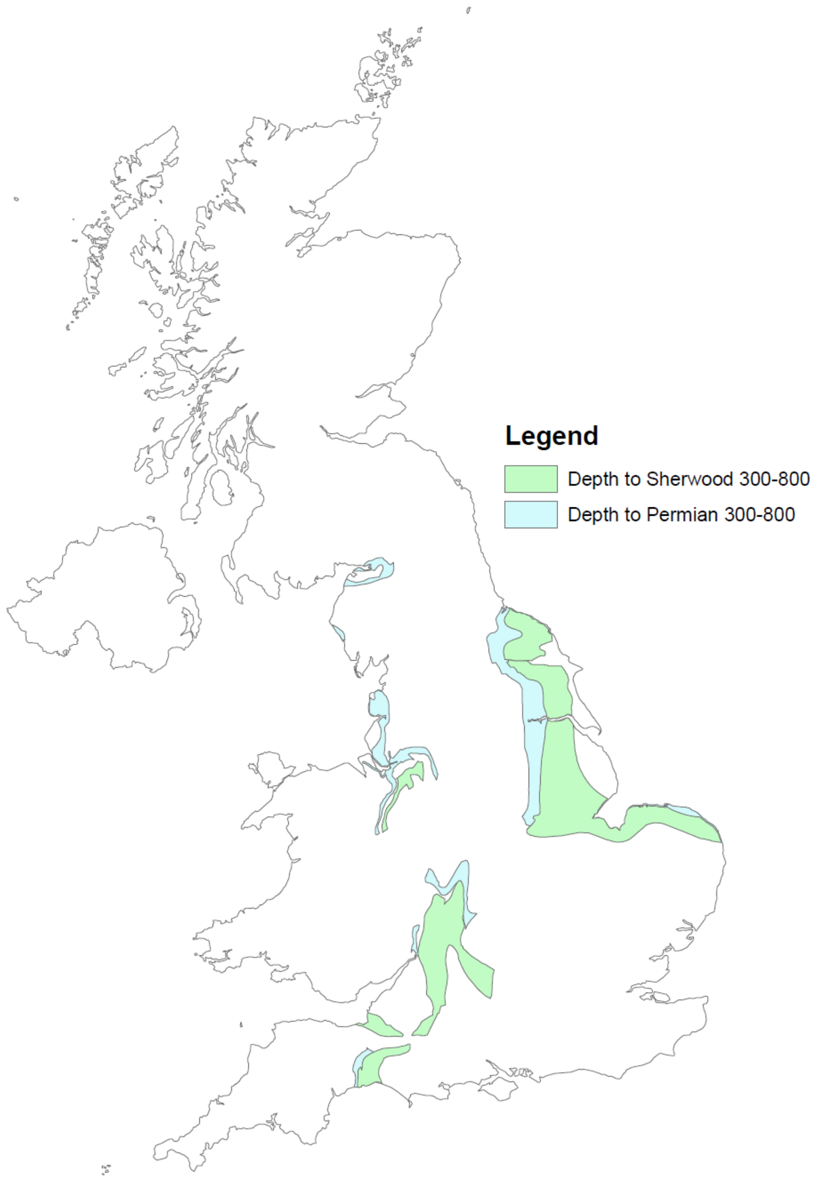

Figure 37 Combined Deep Sandstone Mapping

Well Yield Assessment for Shallow Aquifers in the UK

Using the quoted references shown in Figure 36 it was possible to collate the transmissivity data for each shallow aquifer in England and Wales. In the case of the Chalk aquifer, each region was further broken down into sub-regions. This was due to the huge area each Chalk region covered and the variability of data thereon. For certain aquifer regions and sub-regions more samples have been obtained increasing the level of confidence for mean values. Such regions include West Suffolk, East Norfolk and North Essex in the East Anglian Chalk, and the North West and North East regions of the Permo-Triassic Sandstones. In other regions such as the Vale of Clywd and Flyde in the Permo-Triassic Sandstones and many regions of the Jurassic Limestones, fewer samples have been taken thereby reducing the confidence in the mean transmissivity data.

For Scotland and Northern Ireland no comparable transmissivity data was available but the quoted references provided “typical” yields that have been obtained from the respective aquifers.

The calculated yields using Logan’s approximation for each aquifer are shown in Figure 38. The chalk aquifer would seem to exhibit both the highest mean yields and also a high/ the highest inter-quartile range which suggests a high variability of yield in this aquifer. The highest mean yield (136l/s) is in North Lincolnshire, with further significant yields in Hampshire (93l/s), North Dorset (93l/s), Salisbury (80l/s) and Yorkshire (73l/s). The lowest apparent mean yields are found in the Jurassic sandstones, with the Bristol Channel Upper Lias at 3l/s, and the Permo-Triassic Sandstones, with the South West region offering mean yields of 5l/s. Both these regions have small inter-quartile ranges, 0.3-14.4l/s and 1.7-17.7l/s respectively.

The results seem to show that fractured bedrock systems in England and Wales, i.e. the Chalk, Jurassic Limestones and Magnesian Limestones, have greater yield ranges. This is to be expected due to the inherent randomness of fractures in these aquifers and the coincidental nature of intercepting such fissures when constructing a well. The Lower Greensand and Permo-Triassic sandstones have a smaller inter-quartile range as the transmissivity and yield is now led by a combination of intergrannular and fracture flow.

The mean yield for all the aquifers is 29l/s and the median yield is 15.4l/s. The mean value is skewed by certain higher value chalk sub-regions, so the median yield would seem to reflect a more typical yield found in the UK

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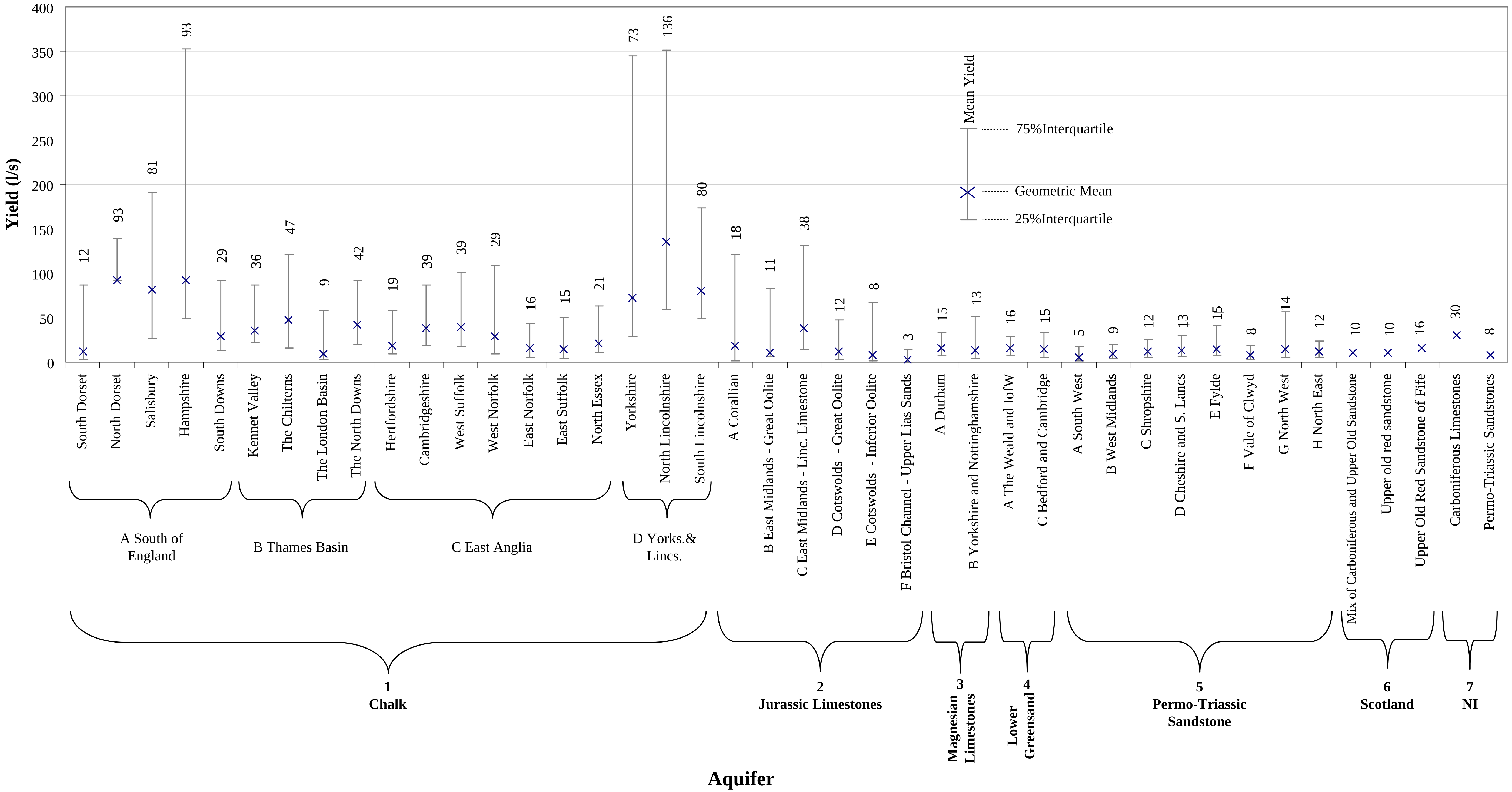


Figure 38 UK Shallow Aquifer Well Yield Assessment, using Logan's Approximation and 10m drawdown

3.6 Summary

3.6.1 Borehole Thermal Energy Storage

The geology throughout the UK varies considerably. Superficial deposits are not generally of great enough thickness to influence the design of a vertical closed loop ground energy storage so the bedrock becomes the dominant geomaterial to consider. Apart from isolated concentrations, the heat flux varies between 40-70mW/m^2, with an average value of 57mW/m^2. Combining the feasible coincidental thermal conductivity and heat flux of bedrocks suggest that the thermal gradient can vary from 0.8 to 6.2K/100m with an average of 2.1K/100m. Again combing coincidental properties it is possible to suggest that the bulk borehole temperature for a 100m deep GLHE can vary from 8.3 to 13.5˚C with an average temperature of 10.7˚C.

Whilst the volumetric heat capacity does not vary significantly from bedrock to bedrock, the thermal conductivity for different geomaterials does vary. Furthermore, the results for certain bedrock types suggest the absolute need for in-situ testing to be carried out due to the significant range in values. This is particularly true of sandstones, mudstones, limestones, mica schists, gneiss, basalts and granites. There is a lack of understanding about how many samples have been taken for each range within the referenced data set. Also, there is no information regarding how the testing was completed, i.e. with what equipment and procedures and at what locations. As the results come from a German publication it is not clear that the range will also be typical in the UK although, by definition, the bedrock may not fundamentally change in composition. Referencing such a publication remains justified in this case in the absence of other suitable country specific data sources and to show the potential influence in design from bedrock to bedrock and location to location.

In the UK, there are regional characteristics for certain bedrock types that could bias values within a tighter band with different typical values. However, not enough data has been made publically available as yet to make this judgement. There is valid discussion to suggest that as vertical closed loop ground energy systems become more popular that data from all thermal response tests should be logged with the British Geological Survey in a similar way to well and common borehole tests. Also, that testing procedures are made standard with certification required for all contractors. For the time being it seems that simply assuming a “typical” value throughout the design process could significantly affect the long term performance if a lower thermal conductivity is realised in-situ.

The spatial implications will be very significant for large scale energy storage where there is limited space available near to the power stations or urbanised areas. This will limit the application for smaller storage systems possible for discrete masterplans and/ or for diurnal storage rather than for mass storage systems.

Also, if there is a need to use typical values for thermal conductivity at the desktop feasibility stage there is a definite need to understand the likely range. A worst case scenario could be used to ensure that the realisation of a lower value during a thermal response test (TRT) does not then invalidate the proposed system and strategy.

Irrespective of the spatial implications, perhaps the most significant impact is on cost. It has not been possible within the scope of the research to gain actual installation quotes for the scale of installations required but it is clear that as the GLHE is going to be a significant proportion of the total installation cost, the length variation according to bedrock thermal properties will make a huge impact.

Due to the limited heat storage potential for large scale BTES systems the modelling and system design is focussed on ATES systems due to the inherent lack of research and precedents in the UK. BTES systems have been identified as a marginal storage strategy only feasible for discrete masterplans or at a building level. In such cases the knowledge and experience of modelling is good both in the UK and around the world.

3.6.2 Aquifer Thermal Energy Storage

The UK has limited potential for open loop systems. It is estimated that only 19.7% of the UK is underlain by “productive” aquifers. According to the methodology used, the range in yield is extremely large, not just between different aquifer types and regions but also within these regions. The range in yield is generally greater for aquifers dominated by fracture flow due to the need to intercept fissures in the bedrock to connect with groundwater flow.

Due to the range in values there remains an inherent risk that assumptions made at the design stage will be higher than realised yields following a site investigation. The analysis focussed on the mean and the inter-quartile range. Reference to minimum values of transmissivity data for each resource highlights that typically high yielding aquifers such as the chalk in the North Dorset and Yorkshire regions can still have extremely low transmissivities. In such instances the yield from the well could be less than 0.1l/s thereby making the corresponding capacity too low to be economically feasible. Therefore, whilst the mean yields from the majority of the aquifers under analysis could prove economically viable the need for a full site investigation is an absolute requirement. In comparison, the key parameters for closed loop systems, although still having the potential to vary considerably, will not approach such low values.

No enough immediate data was available to assess the spatial potential from moderate yielding aquifers. However it is highly likely the mean yield will be lower than that for productive resources, thereby reducing the potential to use for larger storage applications.

No significant data is available to complete a spatial review of aquifer properties for the deeper sandstones.

4 Technology Identification and System Configuration Overview

This section sets out the range of approaches available for distributing the heat energy. It covers above ground system infrastructure and performance with depending on the temperature regime selected for the below ground heat storage.

4.1 Heat take off – Above Ground Infrastructure

4.1.1 Typical heat network using mixed heat sources

A typical 'Danish' district heating transmission system is shown in Figure 39 below. The best known example of this approach is the Danish city of Copenhagen, see Figure 40. This system links heat sources to heat loads up to 50km apart along a network of steel pre-insulated pipework (actual network length is much longer). The following section examines the key parameters in establishing potential models for distributing stored ground energy.

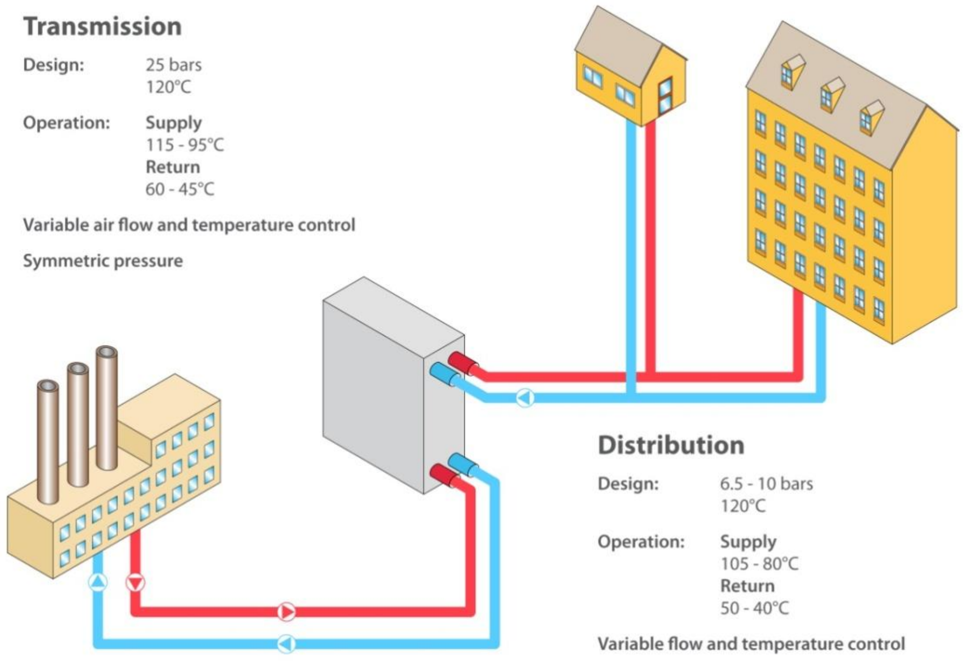


Figure 39 'Danish model' of transmission and distribution level district heating network

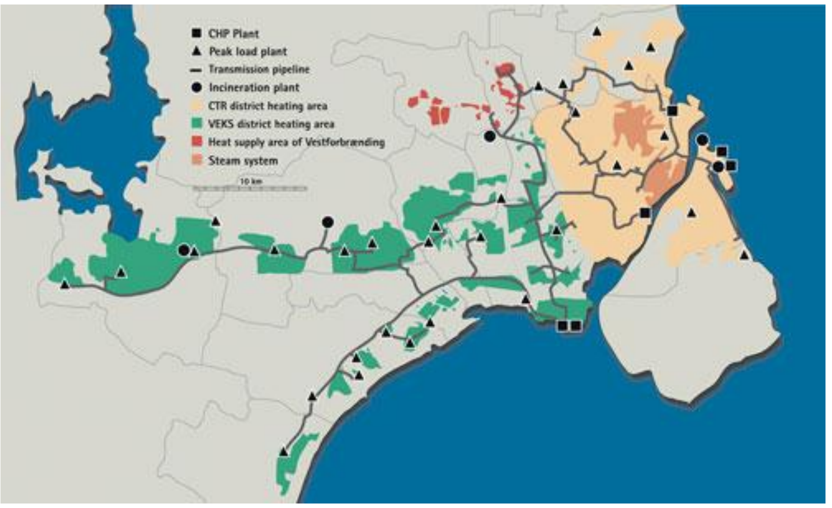


Figure 40 Danish district heating transmission network

4.1.2 Overview of key variables

A number of key variables determine the potential concept designs for the heat take off and transmission and distribution network. These have been captured in Figure 41.

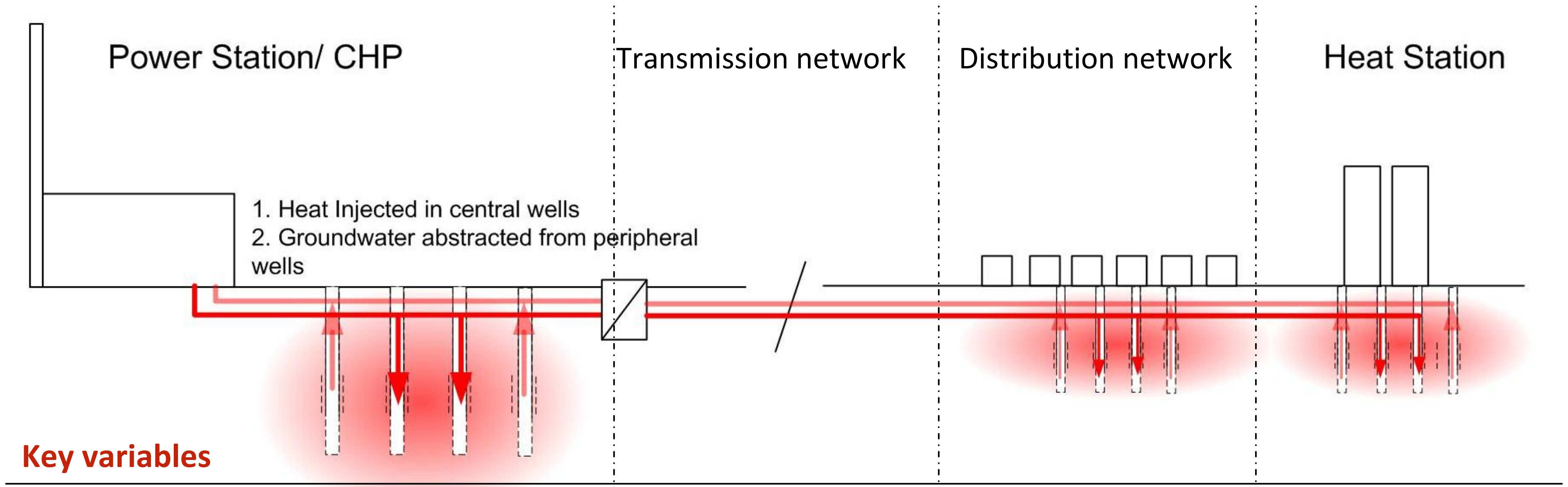
Of these a few are fundamental variables and it is worth noting these when considering the basic combinations:

Heat take off temperature – The temperature of heat supplied into the network from the heat source will have a direct effect on the specification of how the heat is stored and how the heat is transferred from the heat source (in this case, the power station) to the buildings requiring heat.

Supply temperature – The supply temperature to the buildings has to be set at an appropriate value, such that the existing building side heating systems are able to be connected to the heat network with minimal refurbishment work required.

Storage location – The location of the heat storage shall have a direct effect on how heat is delivered to the distribution network. For example, locating a ground heat store local to the distribution network, as well as local to the power station would lead to the possibility of smaller transmission network piping as the heat can be stored local to the load with peak

Heat store capacity - peak load / base load – The capacity of storage shall determine the magnitude of storage required and the type of storage method available. The storage size shall also determine the amount of additional peak plant required in order to produce the peak load, should the storage only be sized for the base load.



Key variables

Ground storage location *(capacity, MWh; extraction rate, MW):*				
	Storage at power station	Storage at transmission level	Storage at distribution level	
Peak load / back-up *(peak load, MW; pipe diameter, mm):*				
	Heat source at power station	Heat source at transmission	Heat source at distribution	Heat source at customer
Diurnal storage *(tank size, m3)):*				
	Storage at power station	Storage at transmission level	Storage at distribution level	Storage at customer
Hydraulic interface *(losses / inefficiency):*				
	Heat exchanger	Heat exchanger / direct connection	Heat exchanger / direct connection	
Operating temperatures *(°C flow and return):*				
Power station	Ground storage	Transmission	Distribution	Customer
Distance to heat load				
(length, m; heat loss, MW/m; load served, MWh):		Transmission system length	Heat density at distribution level	Heat load

Figure 41 Conceptual Heat Take off Model - Key Variables

4.1.3 Temperature Regimes

The brief set by the ETI to consider three temperatures regimes for heat take off, the outline systems are summarised in Table 11 below.

Table 11 Temperatures Considered for the Study

Temperature regime	Heat take off temperature	Comments
High temperature (HTHW)	200 °C	Low/medium pressure steam from: intermediate steam header (low cost modification) Or, low pressure turbine (extract or backpressure)
Medium temperature (MTHW)	120 °C	Medium pressure/temperature hot water As above
Very low temperature hot water (VLTHW)	35 °C	From condenser Diverted flow from the power plant cooling tower

4.1.4 Conceptual models

Based on the noted variables and temperature regimes discussed the following eight conceptual models shown in Table 13, Table 14 and Table 15 have been developed to represent a mix of the most feasible versions of the key parameters.

The Legend for the model diagrams is shown in Table 12.

Table 12 Model Diagram Legend

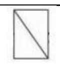
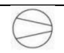
Symbol	Discription
	Pump
	Plate Heat Exchanger
	Heat Pump

Table 13 System Configuration Models 1-3

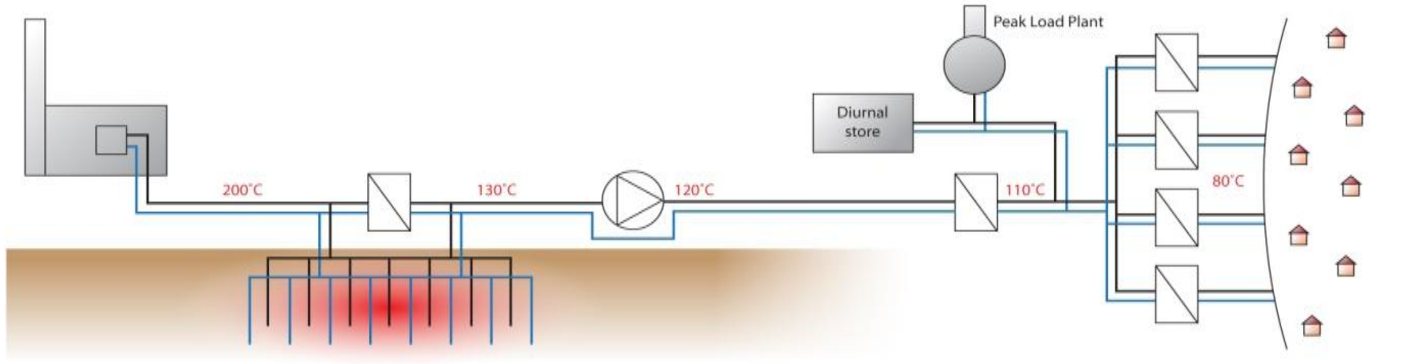
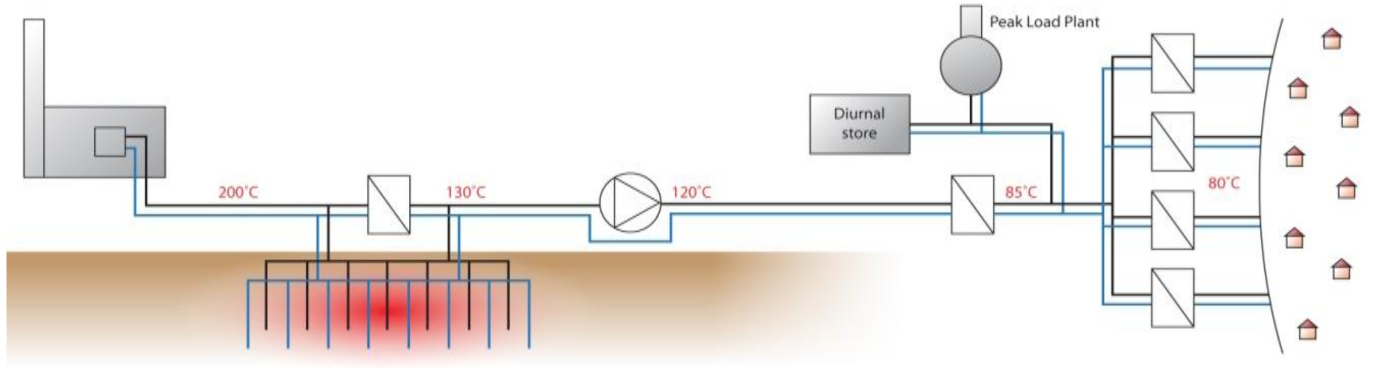
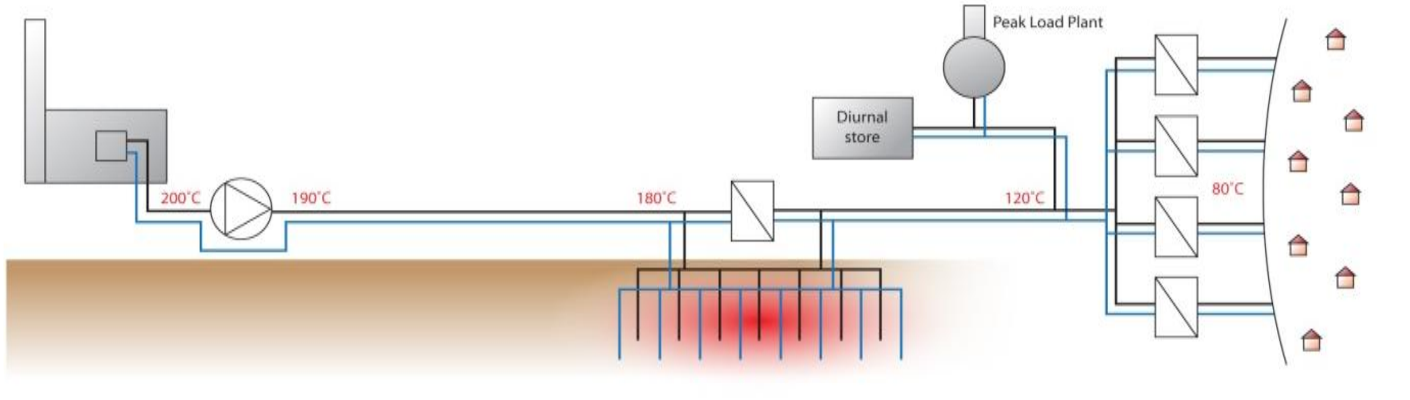
Model 1		**HTHW – High Temperature Distribution - Power plant storage** *Distribution network temperature – 110°C* *District supply Temperature – 95 °C* • Heat stored local to the power plant • Local peak plant provided
Model 2		**HTHW – Low Temperature Distribution – Power plant storage** *District Heating – 85°C* *Supply Temperature – 80 °C* • Heat stored local to the power plant • Local peak plant provided
Model 3		**HTHW - High Temperature Distribution – Local storage** *District Heating – 120 °C* *Supply Temperature – 80 °C* • Heat stored local to the distribution network • Local peak plant provided

Table 14 System Configuration Models 4-6

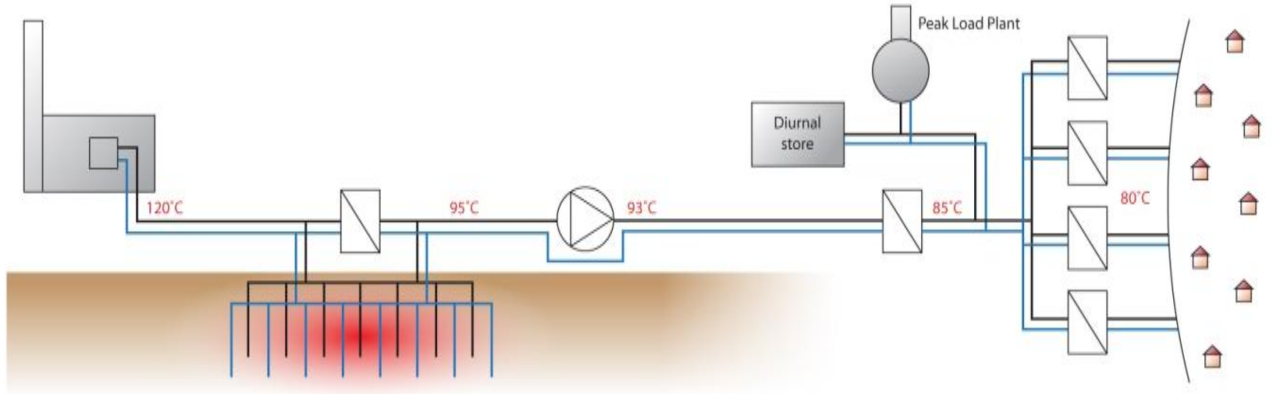
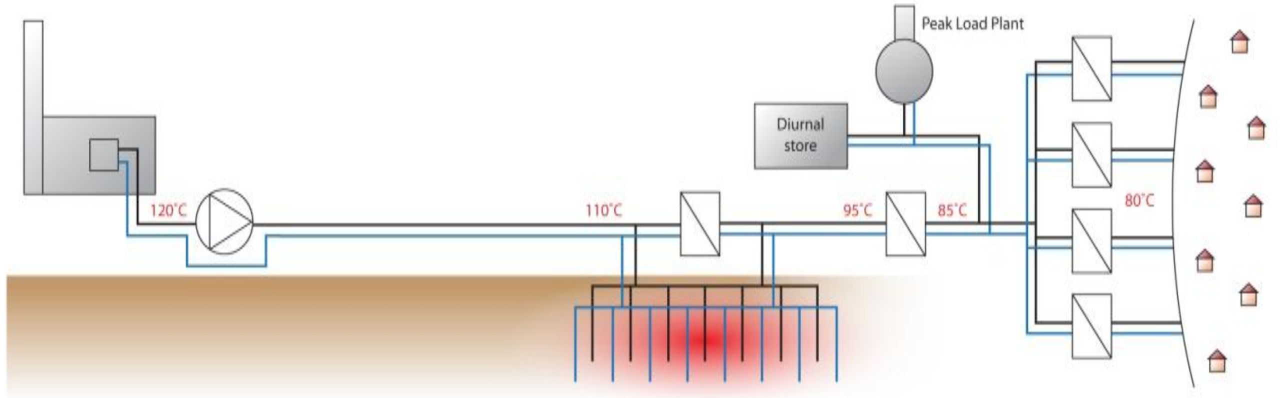
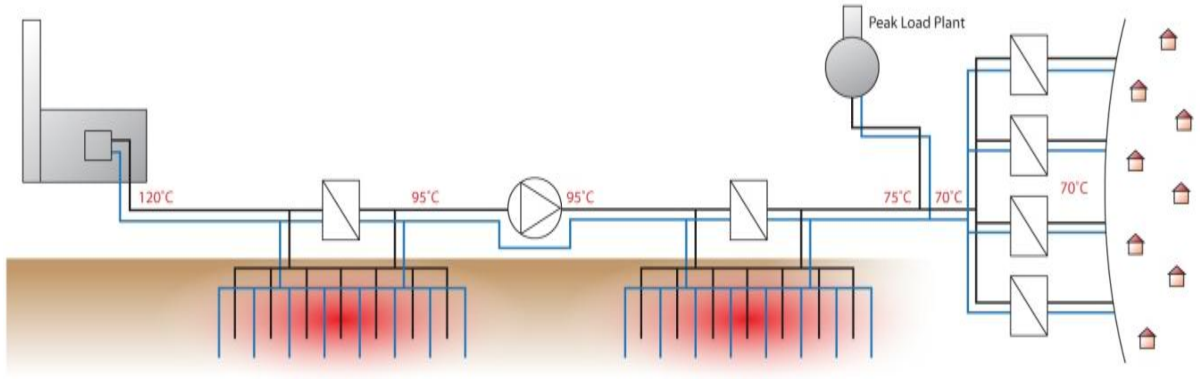
Model 4		**MTHW- Low Temperature Distribution – Power plant storage** *District Heating – 85 °C* *Supply Temperature – 80 °C* • Heat stored local to the power plant • Local peak plant provided
Model 5		**MTHW- Low Temperature Distribution – Local storage** *District Heating – 85 °C* *Supply Temperature – 80 °C* • Heat stored local to the distribution network Local peak plant provided
Model 6		**MTHW- Low Temperature Distribution – Split storage** *District Heating – 75 °C* *Supply Temperature –70 °C* • Heat stored local to the distribution network • Local peak plant provided

Table 15 System Configuration Models 7-8

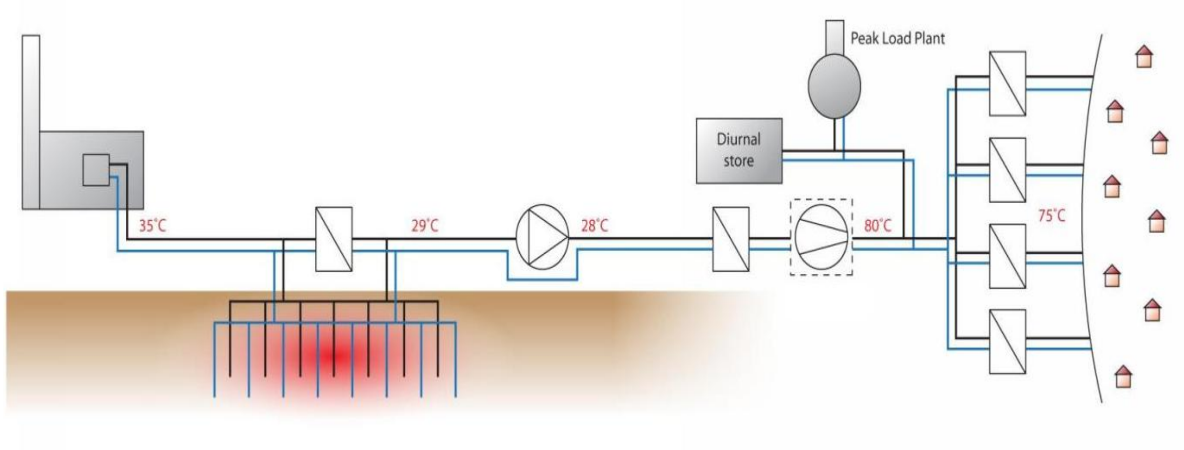
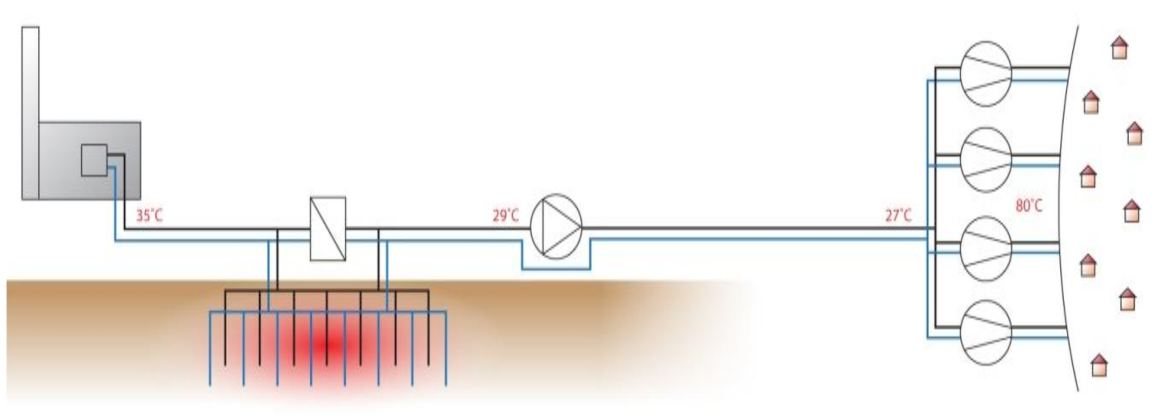
Model 7		**VLTHW- Low Temperature Distribution – Power plant storage – Large heat pumps** *District Heating – 80 °C* *Supply Temperature – 75 °C* - Heat stored local to the power plant - Large Scale Heat Pumps located within the distribution network Local peak plant provided
Model 8		**VLTHW- Low Temperature Distribution – Power plant storage – Individual heat pumps** *District Heating – 85 °C* *Supply Temperature – 80 °C* - Heat stored local to the power plant - Individual Residential/ User Heat Pumps located within individual buildings Local peak plant provided

Table 16 below further expands on the system configurations introduced in the last section, thereby outlining the key opportunities and constraints of each model.

Table 16 Summary of key opportunities and constraints relating to the eight conceptual models.

Conceptual model	Opportunities	Constraints
HTHW		
Model 1	- Supply at medium temperature hot water (suitable for absorption chillers for cooling) - Smaller heat network pipe diameter vs MTHW - High electrical losses in power station (z-factor losses)	- High heat losses in store - High heat losses in network - Expensive pipework/components
Model 2	- Smaller heat network pipe diameter - High electrical losses in power station (z-factor losses)	- High heat losses in store - High heat losses in network - Expensive pipework/components
Model 3	- Supply at medium temperature hot water (suitable for absorption chillers for cooling) - Smallest heat network pipe diameter as peak loads served from local store during winter - Lower store losses than 1 and 2 - High electrical losses in power station (z-factor losses)	- High heat losses in store - High heat losses in network - Expensive pipework/components - Higher network losses than 1 and 2
MTHW		
Model 4	- Supply at low temperature hot water, suitable for most space heating applications - Lower z-factor losses than 1,2 and 3	- Not optimised for absorption chillers - Higher store losses than local storage - Larger pipe network diameter as seasonal peaks met from remote storage
Model 5	- Supply at low temperature hot water, suitable for most space heating applications - Lower z-factor losses than 1,2 and 3 - Lower store losses than 4 - Smaller diameter pipe on transmission main as this runs as base load or store charging	- Not optimised for absorption chillers
Model 6	- Supply at low temperature hot water, suitable for most space heating applications - Lower z-factor losses than 1,2 and 3 - More flexible operations	- Not optimised for absorption chillers - Additional losses from 2 stores
VLTHW		
Model 7	- Low network losses - Low store losses	- Needs heat pumps to supply space heating and hot water to all but the most thermally efficient systems - Carbon balance will depend on heat pump COP, versus losses etc
Model 8	- Low network losses - Low store losses	- As 7 - Less efficient heat pumps due to smaller consumer scale units

4.1.5 Key issues relating to temperature regimes

With each of the temperature regimes chosen for further investigation there are numerous issues and considerations which must be understood, in order to determine the ideal systems options moving forward. Table 17 sets out the key considerations for each of the regimes.

Table 17 Summary of key issues relating to operating systems at the three temperatures regimes.

Issue	HTHW	MTHW	VLTHW
Safety issues from leaks	Leak would flash to steam. Highest danger of burns.	Leak would flash to steam in transmission side of system.	Limited implications from leakage in terms of safety/burns
Heat take off temperature	Highest loss in steam turbine efficiency due to reduction in the enthalpy drop across the turbine	Some efficiency losses from steam turbine. Likely to be z-factor of around 5 (1 unit of electrical power lost for every 5 units of heat take off), but could be around 10 if specifically designed as CHP plant	Minimal/no loss in turbine efficiency (may be some slight loss if condenser backpressure is increased)
Heat supply temperature	Serve space heating, hot water and space cooling (absorption chiller) loads Could be steam network system	High enough to serve most low temperature hot water space heating systems (typical UK system design is 82 °C flow, 71 °C return)	Only capable of supplying heat to underfloor heating (and probably too low even for this). Will require heat pumps to reach useful temperature almost all existing buildings Temperature difference across flow and return needs to be tested, as if this needs to be lower to serve heat pumps, network size and pumping costs are increased
Network losses	High network heat losses, especially on a high temperature distribution network. Transmission network losses likely to be less significant	Network losses as per standard district heating system	Very low network losses (depending on pipework spec)
Storage location	If steam temperatures used limited distance to loads. Otherwise flexible.	Flexible	Flexible.
Diurnal storage	Would need to be pressurised if above 95 °C	Can be un-pressurised and used to provide expansion and static pressure to network	As per MTHW
Controls/valves etc	Higher specification equipment required due to higher temperature	Standard district heating specification equipment	Lower specification equipment could be used e.g. from water industry

Issue	HTHW	MTHW	VLTHW
Pumping	High specification pump materials required due to higher temperatures (e.g. stainless steel impellers) Pump rotating sealing more difficult	Standard district heating specification equipment	Lower specification equipment could be used e.g. from water industry Pump loads could be higher if smaller delta T is required due to heat pump operation
Pipework materials	Requires higher specification pipework due to higher pressures required to maintain pressurised hot water, or steam	Standard steel pre-insulated pipe in HDPE covering. Opportunity to use flexible piping for small diameter distribution network sections.	Could be plastic pipe due to low temperature and pressure
Hydraulic interfaces	Likely to be indirect connections if using high temperatures	Can have direct or indirect connections across the system. Former allows more efficient temperature regimes, latter provides separation of water quality and ownership	Likely to require direct connections to minimise temperature losses across heat exchangers
Water quality	May require higher water quality than MTHW system	As per standard heat network system – pH and de-oxygenation treatment	As per MTHW

The key conclusions contained relating to operating systems at the three temperature regimes are:

- There are high heat losses from storage / transmission associated with the HTHW systems
- Pipework and fittings become more expensive when considering a high temperature system/ as the temperature of the heat take off increases
- The HTHW system would result in high losses of electrical production from the power station due to the Z factor (the Z-factor indicates the amount of power production lost to every unit of heat removed from the power station during the steam turbine cycle)
- The HTHW system is an unprecedented storage temperature. There is substantial world experience of MTHW and VLTHW storage
- The VLTHW option presents the smallest reduction in electrical output from power stations in order to produce heat
- The VLTHW system would require heat pumps, which can be expensive given the probable size of units required, in order to lift the low temperature of the heat take off to that of a usable heating / domestic hot water (DHW) generating temperature
- The MTHW option would lead to the optimum supply temperatures for heating / DHW generation without the need for heat pumps
- There is no clear benefit of the HTHW option for a district heating network, i.e. 120 °C (MTHW) is sufficient for flow temperatures of 80 to 85 °C

4.1.6 Chapter Summary

Within this chapter the configurations of the system and temperature regimes have been explored. The headline conclusions are:

- The HTHW system should be discounted from further consideration due to cost, technical and electrical power production losses
- There is no clear benefit of the HTHW option for a district heating network, i.e. 120 °C (MTHW) is sufficient for flow temperatures of 80 to 85 °C
- There is substantial past precedence for the MTHW and VLTHW storage options

5 Development of an Operational Model

5.1 Overview

An important aspect in an underground heat storage project is the storage efficiency. The storage efficiency is defined as the relation between the amount of energy extracted during the "heating season" and the amount of heat injected during the "recharge season". The thermal efficiency is therefore influenced by the heat losses and in a high-temperature heat storage, these occur due to:

1. heat exchange with upper and lower layers
2. heat transfer by free convection and conduction
3. thermal dispersion

To analyse the relative impact of differing parameters, sensitivity analysis has first been completed to quantify and assess the role of each parameter in a homogeneous aquifer on the storage efficiency. Following the conclusions of this work some initial analysis is used to consider the effects in a heterogeneous aquifer where the permeability varies with depth according to e.g. less or more dense bedrock, impermeable marl bands etc.

The focus of the modelling work has concentrated on the 120°C injection temperature. Considerable validation work has been completed on lower temperature regimes so for the purposes of this interim report it was considered more useful to review the potential of medium temperature heat storage.

5.1.1 Introduction

When fluid migrates through a permeable rock the temperature field typically lags behind the fluid front owing to the effects of thermal inertia. Thermal inertia arises because on the pore scale, the fluid and the rock grains tend to equilibrate thermally since the time for conduction of heat through a grain is much shorter than the typical residence time of fluid as it passes through the pore space in contact with the grain. As hot fluid is injected into a porous medium, the fluid will therefore heat up the grains near the injection well, and the injected fluid ahead of this will cool to the formation temperature.

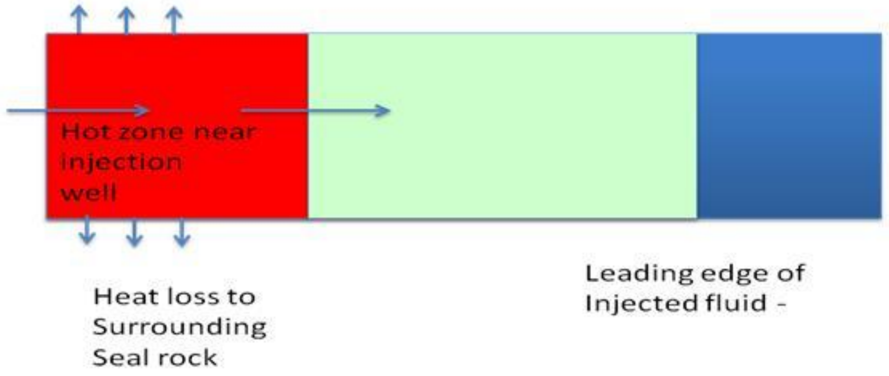


Figure 42 Cartoon of flow invading reservoir, with hot injection fluid cooling to the formation temperature at some distance into the reservoir upstream of the front with the cold reservoir fluid.

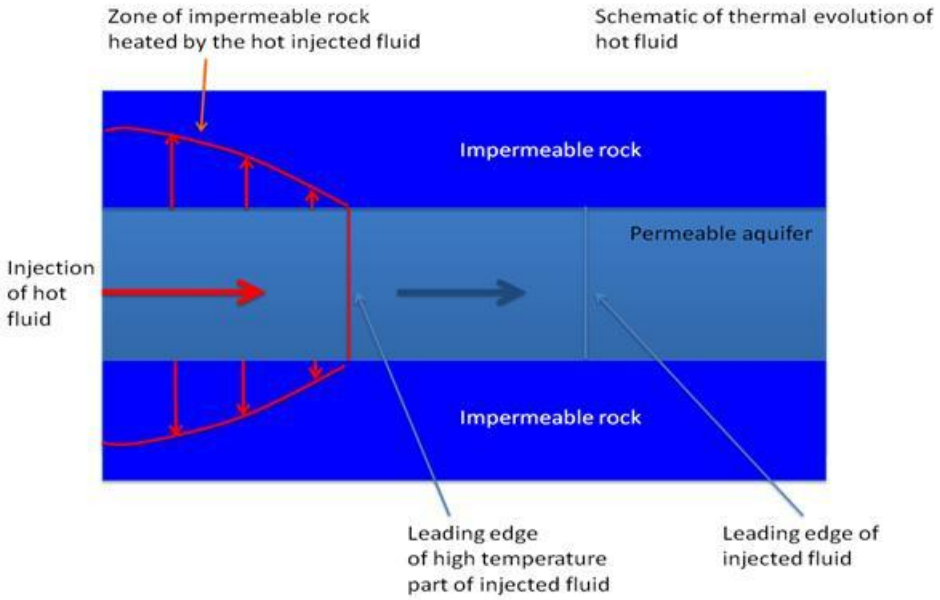


Figure 43 Illustration of the zone of heating around the permeable aquifer, with relatively low flow beyond the aquifer.

In a uniform permeable rock, this will lead to an equation for the migration of the thermal signal through the formation of the form:

$$\frac{\partial\theta}{\partial t}+\Gamma u\frac{\partial\theta}{\partial x}=\kappa\left[\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}\right]$$

where Γ is the speed of the thermal front as a fraction of the interstitial speed u/ϕ where ϕ is the porosity and u is the Darcy velocity (ie the transport velocity). Here x is the direction of flow and y is the direction normal to this (in a 2 D flow).

As the fluid migrates through the rock with speed u/ϕ , it follows that in the absence of the diffusion/dispersion , denoted by the term with coefficient κ in the above equation, then the thermal front is a sharp front located at a fraction Γ of the position of the injected fluid front (Figure 42).

5.1.2 Dispersion

It follows that with an oscillatory flow field, the hot fluid will migrate into the rock on injection, and may then be recovered at the injection temperature from the site of injection, by reversing the flow. However, the thermal diffusion/dispersion acts to spread out the thermal front and therefore reduces the efficiency of the system. Diffusion of heat occurs both in the direction of flow and in the direction normal to the flow, and leads to a heating of the rock beyond that region invaded by the injected fluid. As a result of this, the recovery temperature of the fluid will be lower than the injection temperature, since there is a net heat input to the system. In many natural rock systems, the formation will have a non uniform permeability so that there are zone with greater flow than other adjacent zones. Thermal diffusion can act across these zones, leading to heating of the slower moving fluid and associated rock, by the warmer fluid (Figure 43 and Figure 44).

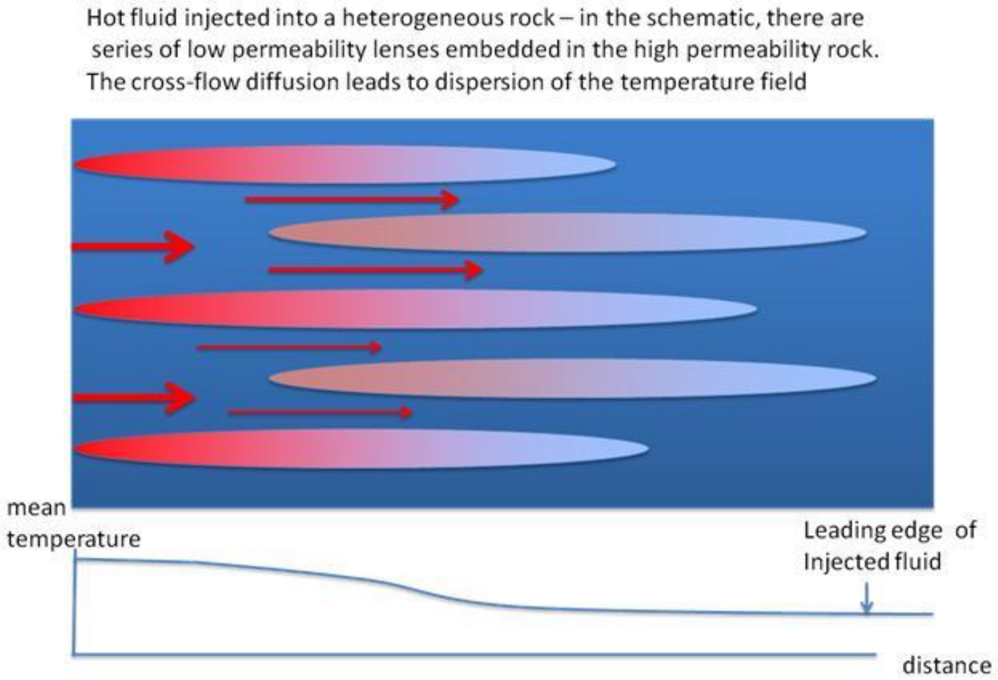


Figure 44Illustration of how local low permeability baffles can change the flow speed and introduce cross-flow temperature gradients. In turn these exchange heat with the warm injectate, and lead to an effective dispersion in the system.

With an oscillatory flow field, the heat which is diffused normal to the flow during the injection phase can then be transferred to the colder formation fluid during the production phase. As the next phase of injection occurs, the warmed formation fluid then transports this thermal energy further into the formation, leading to a net transport of heat beyond the zone in which the injection fluid is located. Over a series of injection-production cycles, this is expected and this would lead to a net transport of heat into the formation, as the region near the injection site is continually heated (Figure 44). In early years, this cycling of the thermal energy, and transport deeper into the reservoir will lead to relatively low recovery temperatures of the fluid during the production phase. However, as the reservoir heats up and the temperature gradients in the field decrease, the effectiveness of this transport decreases and so the recovery temperature will tend to increase.

The net effect of the cross-flow diffusion of heat between the regions of high and low flow rate is to cause an effective longitudinal dispersion of the thermal field as the non/slower-flowing zones try to thermally equilibrate with the faster flowing zones. A balance is established between the transport of the thermal energy along the temperature gradient in the fast flowing zones, and the cross-flow conduction of this thermal energy in the cross-flow direction.

The net dispersion coefficient then scales as:

$$\text{Disp} \sim \frac{(\Delta u d)^2}{D}$$

where the velocity fluctuations Δu act over a zone of thickness d. With the oscillatory frequency, the thickness of formation which can thermally equilibrate over one period of oscillation, and hence transport heat scales as:

$$d \sim (\kappa/w)^{1/2}$$

Combining these two relations, it is possible to infer that the anomalous dispersion associated with the oscillatory flow has a coefficient which scales as:

$$\text{Disp} \sim \frac{\Delta u^2}{\omega}$$

5.1.3 Model Predictions

In order to illustrate the significance of this dispersion, superimposed on the oscillatory flow field, we have carried out a series of calculations of the radial counterpart to equation (1) for injection from a central well into a reservoir of finite thickness in the long time limit, of many injection cycles, to explore how the thermal field in the rock and the recovery temperature evolve with time in the limit that there is a well which is used for injection and then production.

We specify that the velocity varies as a sinusoid to illustrate some of the key points concerning the distance the thermal field advances into the reservoir. Here we use typical values for the advection and diffusivity, by considering an injection rate of 0.01 cu m/s into a 100m deep layer.

Figure 45 shows how the temperature field evolves in time from the initial cold temperature to progressively warmer system after 4, 7 and 10 years of injection. In the figure temperatures are defined in a dimensionless fashion for convenience: we plot the ratio of the temperature at the production well relative to the background reservoir temperature compared with the injection temperature relative to that of the formation.

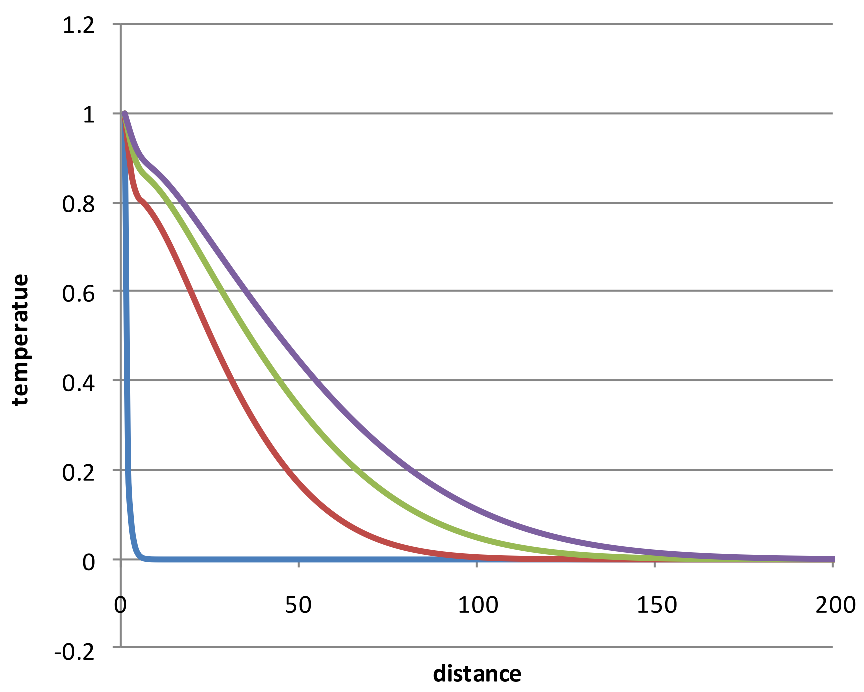


Figure 45 Thermal profile in the formation at times 1 year(blue), 4(red), 7(green) and 10(purple) years. The reservoir continues to heat up over this time

The temperature warms up a progressively larger zone of rock owing to the thermal dispersion in this oscillatory flow field. At the producing well, the temperature also fluctuates between the injection value, set to be 1 in non-dimensional terms in the above model and lower values closer to the formation temperature, which is set to have temperature zero in the above model.

Indeed on each production phase, the temperature falls back from the injection value as the fluid from further into the reservoir, as lower temperature is drawn into the well.

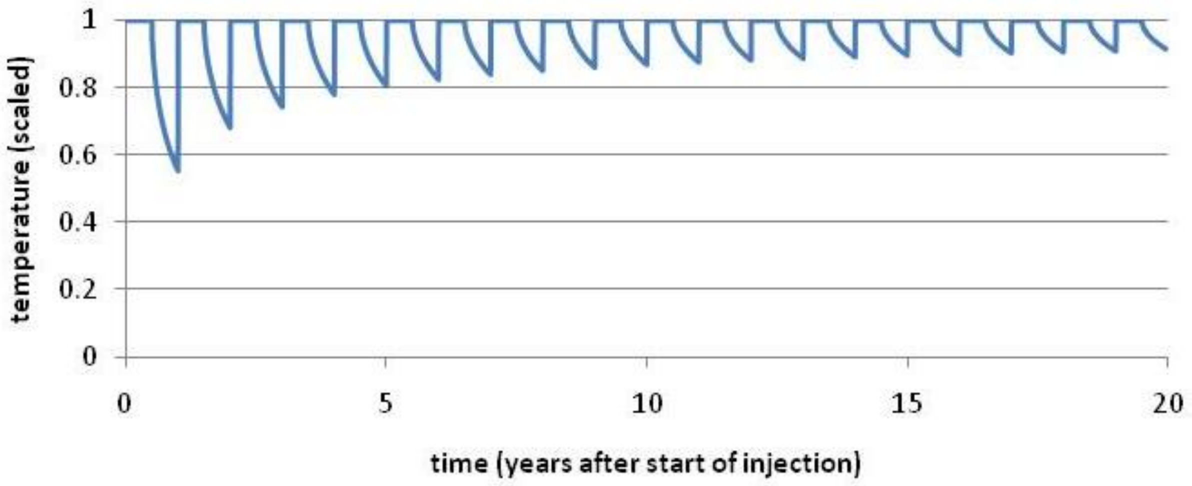


Figure 46 Variation of the well temperature as a function of time. The well temperature decreases during each production phase as fluid from further into the formation migrates towards the production well. The magnitude of this decrease becomes smaller on each cycle as the reservoir overall heats up

Figure 46 shows how the recovery temperature becomes progressively warmer with time, as expected, although overall it is below unity, and hence heat is being lost to the ground each injection phase. Initially, the produced water could be rather cold, as in years 1 and 2 above, but subsequently the water heats up and only cools a small amount, as the near-well rock is also heated up.

A key issue here is whether the temperature of the produced water falls sufficiently compared to the useful temperature that the water requires a thermal boost at the surface using a heat pump.

It is possible to test the sensitivity of these calculations to the specific values used for the injection rate and the thermal dispersivity of the formation. In the above calculations, it has been assumed that the dispersivity has a value of 10^{-5} m^2/s as a result of the presence of low permeability zones within the formation. (note: it is also assumed implicitly in the modelling that the heat loss to the formation beyond the flowing aquifer is small)

If the dispersivity was smaller, the thermal signal does not disperse as far and the heat storage becomes more efficient, as shown in Figure 47 and Figure 48 below, where we see that after 10 years of injection, the thermal signal has not advanced as far into the rock compared to Figure 45 and Figure 46, and that the temperature of the produced fluids is higher at a given year after the start of the process.

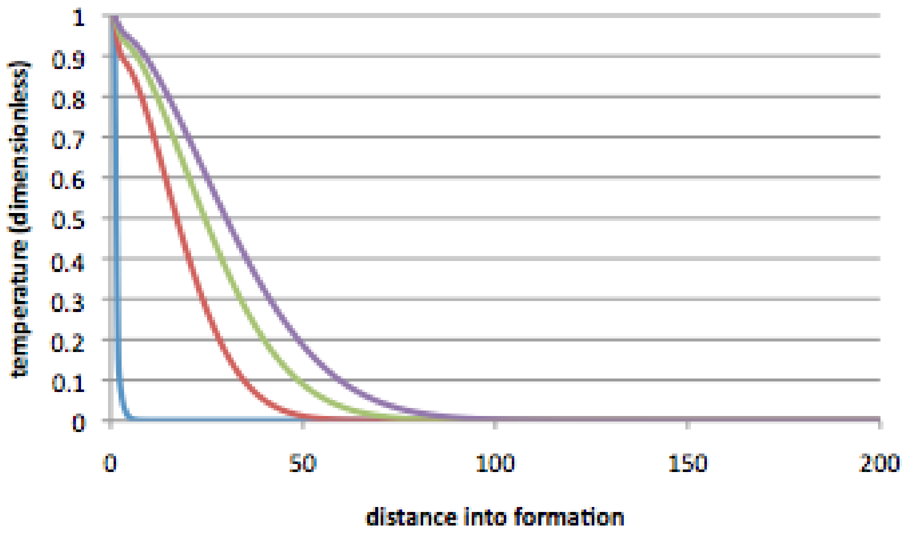


Figure 47 Thermal profile with a dispersivity of 0.25 of the value in the earlier model calculation

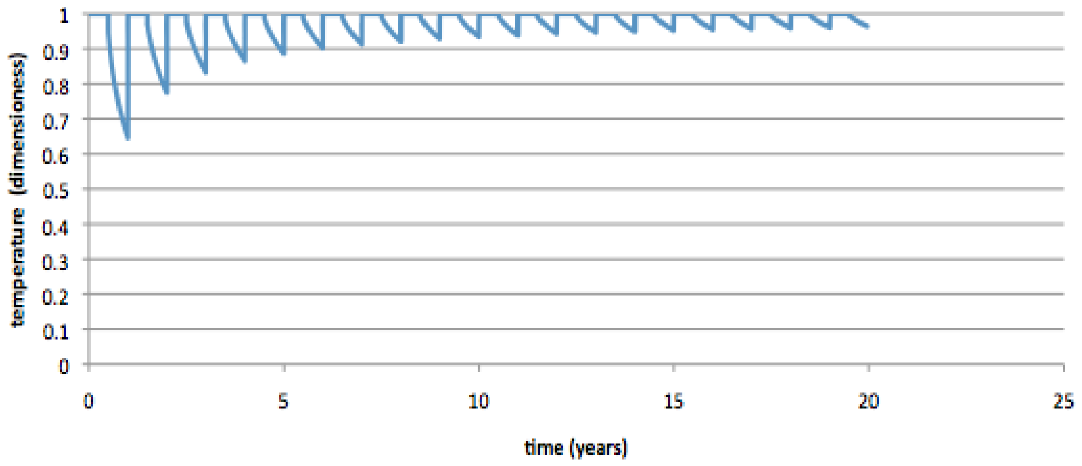


Figure 48 Production temperature each year showing how the temperature rapidly rises towards the injection temperature owing to the reduction in temperature gradients with time in the formation.

5.1.4 Multiple Flowing Zones

In the calculations so far in this section it has been illustrated how the heterogeneity of an individual layer may lead to dispersion of the thermal field, and hence spreading of the temperature field beyond the immediate zone which is flooded with the injection water. This effect is a local process, and the impermeable or zones of reduced permeability need to be sufficiently close to the flowing layer in order that the heat transfer occurs during the injection-production cycle.

However, if there are larger regions of heterogeneity, for example associated with multiple macroscopic flow layers, separated by some impermeable rock, then the flow will advance a different distance along each layer and the associated dispersion will also change. If the different layers are sufficiently far apart (10m or so) that over a decadal time scale they remain thermally isolated then the thermal front will evolve rather differently in the different layers given the same source pressure. The sensitivity to flow rate in a given layer is illustrated in Figure 49, in which the thermal profiles and the recovery temperatures in a much less permeable layer are shown for comparison with Figure 45.

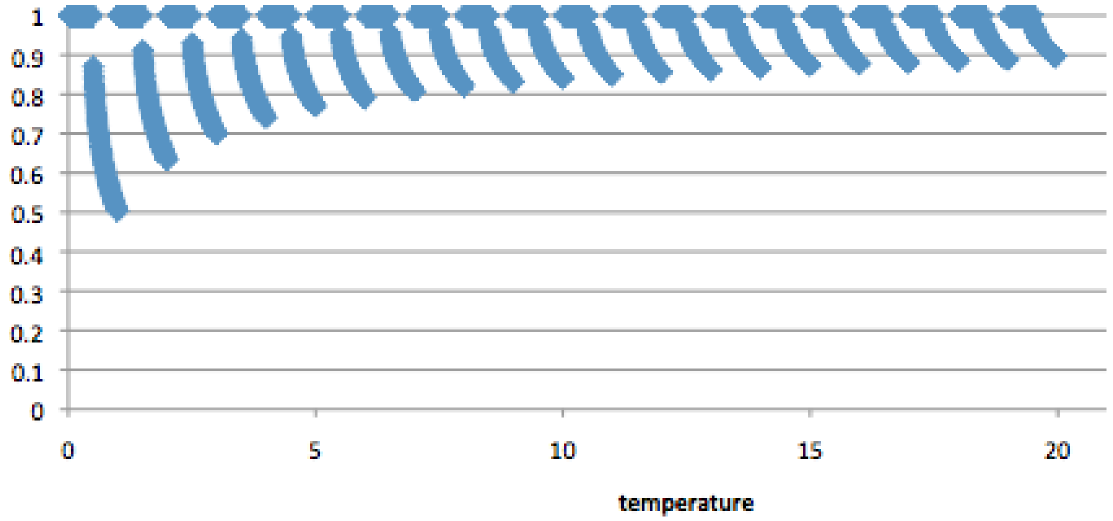


Figure 49 Analogous to figure 3, except the velocity and the diffusivity are 4 times smaller. This leads to shrinkage of the region affected by the injection. The recovery temperatures are lower in this slower flow domain, as more heat is able to diffuse from the heat source than is being injected.

In order to estimate the flow from a macroscopically multi-layer system, the average flow for each layer is estimated as above, and the weighted average production temperature can be found. This combined with the distribution of the permeability of the layers in the system enables a statistical estimate of the mean recovery temperature in the system to be made.

5.1.5 Buoyancy Effects

In the discussion above we have neglected the effects of buoyancy on the flow, and instead focused on the role of dispersion within layers. However, in addition to this, in a thermal storage aquifer, up to several hundred metres in depth, the difference in density between the injected and the reservoir fluids, which results from the temperature difference, can have a key control on the flows. If the reservoir is layered then the buoyant flow will tend to run along the upper part of the formation (Figure 50). On production of the flow, as hot fluid enters the well, the pressure gradient in the system changes, and this may lead to preferential production of the colder denser fluid deeper in the reservoir, since there is an additional head acting on this flow in the production mode.

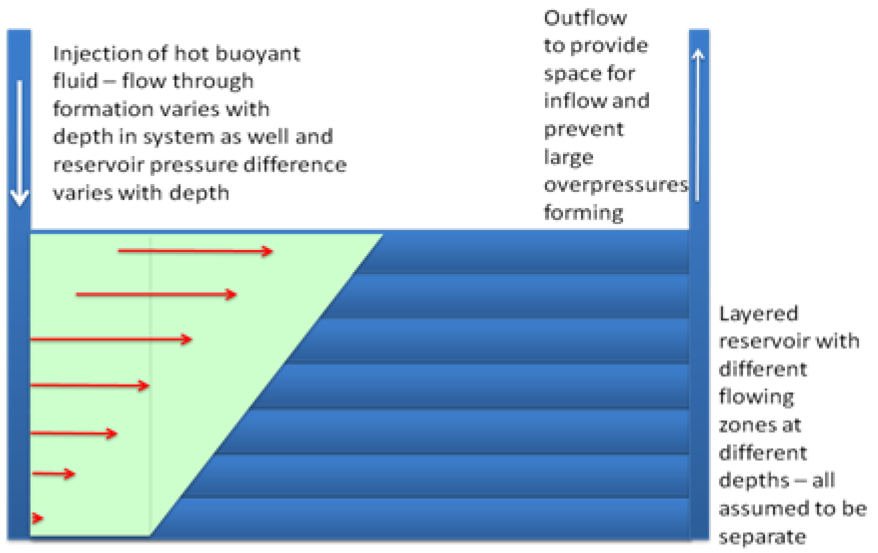


Figure 50 Illustration of the flow focusing in the upper part of the reservoir under buoyancy dominant flow

In order to quantify the effects of the buoyancy in dispersing the flow in a layered reservoir, a simplified model has been developed, in which we assume the flow is driven along each of the layers by the pressure gradient associated with the buoyancy drive in addition to the background applied pressure.

We suppose the reservoir is of vertical extent H and depth D below the surface, and the excess temperature of the injected fluid leads to a reduction in the density of $\Delta\rho$ relative to the background. We also assume the pressure at the base of the injection well is Δp in excess of the hydrostat at that depth. Then at a distance y above this, the pressure will be approximately $\Delta p + \Delta\rho g y$ in excess of the hydrostat.

As a result, in a layered system, the inflow at height y above the base of the well will occur at Darcy speed:

$$u = \phi \frac{dL}{dt} = -\frac{k}{\mu}\left[\frac{\Delta p_i + \Delta\rho g y}{L_p}\right]$$

where L(y) is the lateral extent of the injected fluid in a system with many horizontal layers separated by shales/seal rock.

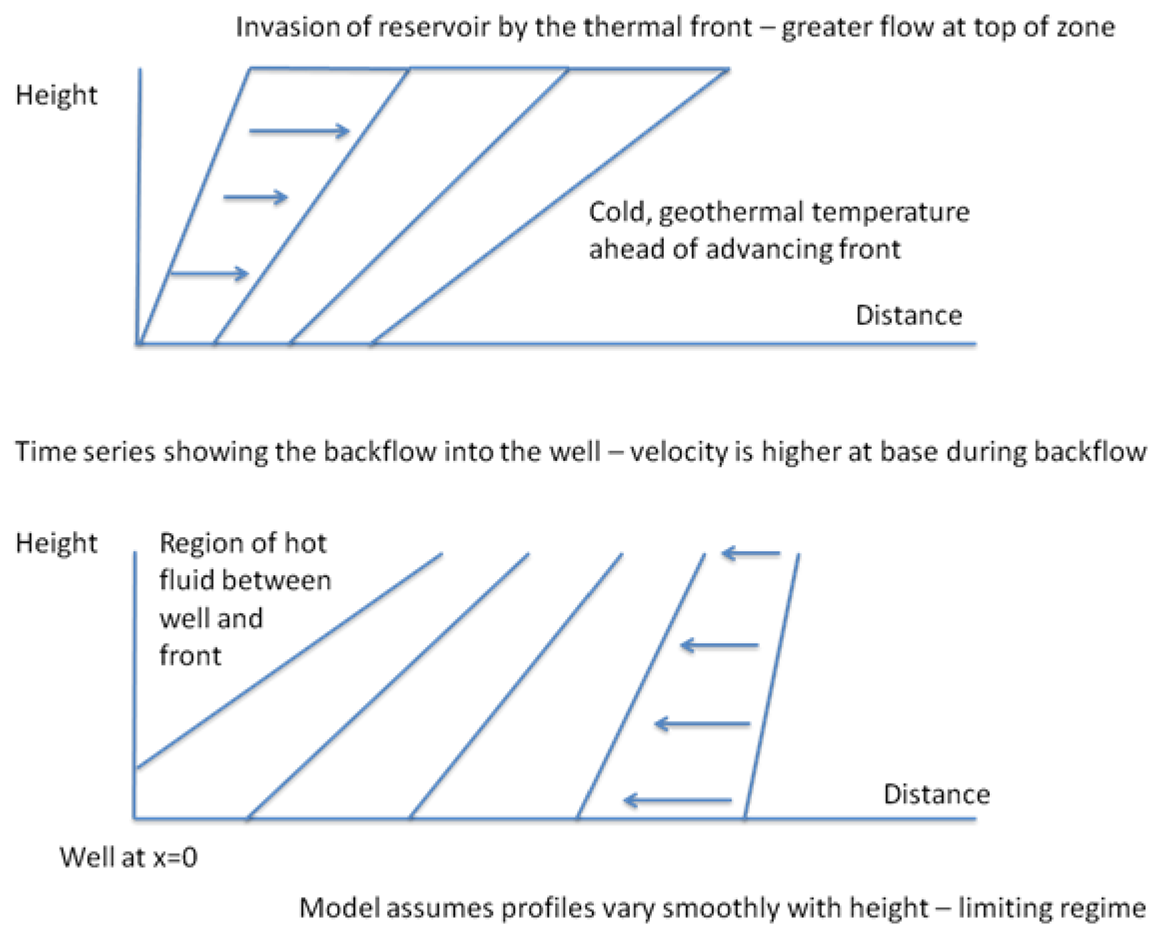


Figure 51 Schematic of the velocity profile in the injection and production regimes

If the injection continues for a time t then the thermal front invades a distance:

$$L = \left[\Delta p_I + \Delta\rho g y\right]\frac{k\tau}{\Gamma\mu L_p}$$

If this fluid is back produced from the reservoir, through the same well, as a model of a huff-puff system, in an attempt to minimise the dispersion of the thermal signal, then if the base of the well is underpressured to a value Δp_o

the flow at each point y above the base of the reservoir will back flow a distance:

$$L = \left[\Delta p_o - \Delta\rho g y\right]\frac{k\tau}{\Gamma\mu L_p}$$

if backflow persists for time t. As a result, at intermediate times t during the recovery phase, the extent of the hot zone at depth y in the reservoir is:

$$X = \frac{k}{\Gamma\mu L_p}\left[\Delta p_I\tau - \Delta p_o t + \Delta\rho g y(\tau + t)\right]$$

If the extract volume matches the injected volume, then as a simplification, if we assume the well-bore remains hot during the extraction, we find that the magnitude of the under pressure of the reservoir:

$$\Delta p_2 = \Delta p_1 + \Delta\rho g H$$

As a result, the time at which the thermal front at height y above the base of the reservoir flows out the reservoir is given by:

$$t = \left[\frac{\Delta p_1 + \Delta\rho g y}{\Delta p_1 + \Delta\rho g(H - y)}\right]\tau$$

This reaches the value t when y=H/2, so that the lower part of the reservoir becomes fully flooded with water at the original reservoir temperature while the upper part of the reservoir remains hot after fluid has been produced for a time t. The fraction of the injected thermal energy remaining in the reservoir at this stage is then given by:

$$\text{Fraction} = \frac{\Delta\rho g H}{2(2\Delta p_I + \Delta\rho g H)} < 0.5$$

With multiple injection cycles, assuming the same pressure distribution, then this fraction of the total heat injected remains in the formation, leading to a cumulative heating of the subsurface.

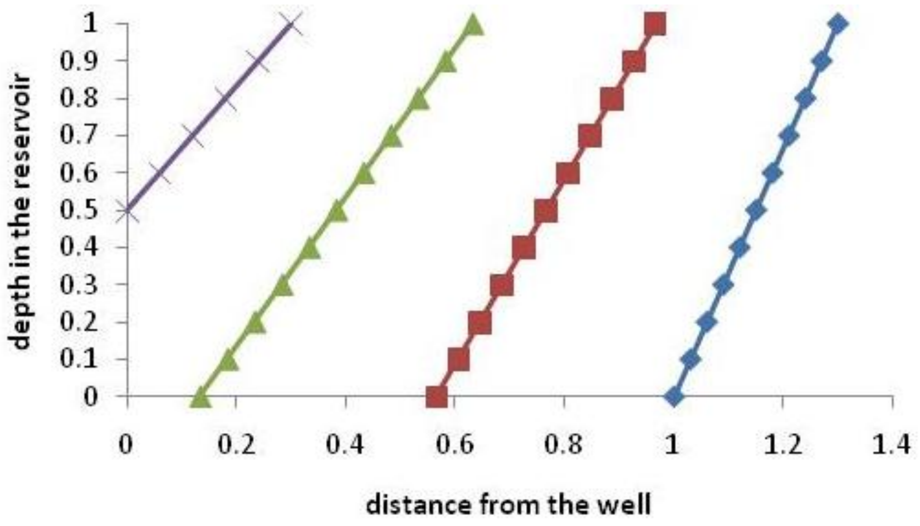


Figure 52 Model calculation showing how the hot zone which has a sharp interface with the cold zone in this model (initially the dark blue line with diamonds) wanes in time once the production commences at the well at x=0.

Ultimately the interface migrates to the source. The fluid in the region between the x-axis and the purple line is not produced from the reservoir but is lost to the rock – this loss has a fractional value given by the area of the purple triangle and the area between the blue line and the y axis.

In addition to the loss of heat owing to the asymmetry between the injection and the production process, one aspect of interest concerns the temperature of the recovered flow as a function of time. Initially, the recovered flow has the same temperature as the injected hot water.

However, once the thermal front flows back to the well at the base of the formation, the fluid which is subsequently produced from low levels has the reservoir temperature and this lowers the overall temperature of the recovered flow, so that:

$$T = \frac{T_I(H-y) + T_R y}{H}$$

where y is the level in the reservoir at which the hot fluid front just reaches the well given in terms of the time t as

$$y = \frac{\Delta p_I(t-\tau) + \Delta\rho g H t}{\Delta\rho g(t+\tau)} \quad \textbf{for} \quad \tau > t > \left[\frac{\Delta p_I}{\Delta p_I + \Delta\rho g H}\right]\tau$$

This leads to a reduction in the temperature of the produced fluid with time of the form:

$$T = T_I - (T_I - T_R)\left[\frac{\Delta p_I(t-\tau) + \Delta\rho g H t}{\Delta\rho g H(t+\tau)}\right]$$

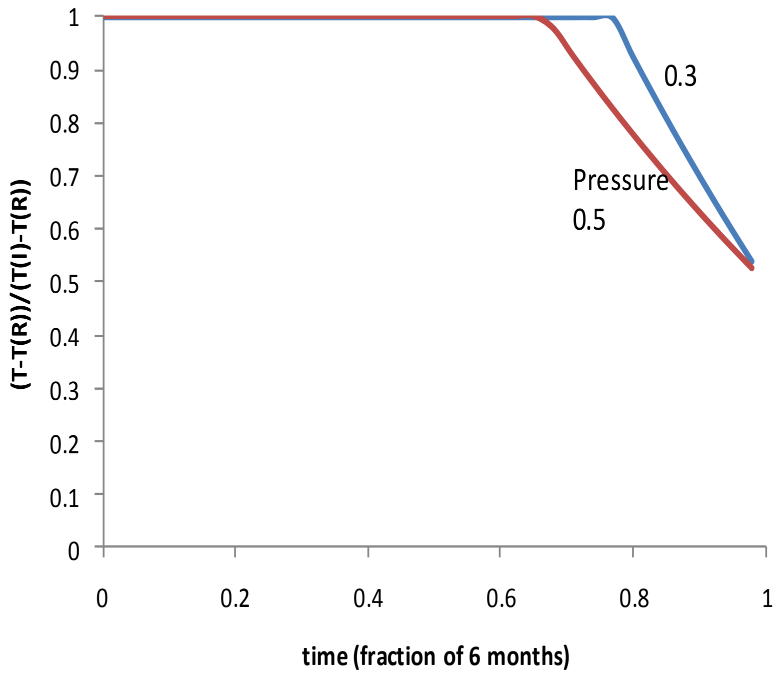


Figure 53 Illustration of how the temperature of the produced hot fluid varies in time owing to the difference between the inflow and the outflow dynamics described above.

By referring to Figure 53, in a 6 month period of production, the temperature begins to falls from the injected temperature in the last 1-2 months, as some of the cold fluid begins to break through into the well. The drop in temperature is quite rapid, and depends on the intensity of the flow. The numbers 0.3 and 0.5 denote the relative strength of the driving pressure compare to the hydrostat.

5.1.6 Summary

In this section of the report it has been described how the thermal front migrating into a porous layer lags behind the fluid front and changes the temperature of the matrix. We have shown that with an oscillatory flow, on the multi-year time-scale, dispersion arising because of the presence of heterogeneities can lead to a spreading of the thermal front and heating of a much larger volume of rock. In turn this impacts the temperature of the produced fluid. As more heat is stored in the rock, less heat is available for recovery, and the recovery temperature falls. However, with multiple injection cycles the recovery temperature drifts upwards owing to the weakening of the temperature gradients as the system heats up.

5.2 Homogeneous Aquifer Analysis

5.2.1 Methodology

Preliminary calculations indicated that the main heat losses will occur due to free convection. In a free convection regime, the flow pattern (and hence the heat transfer) is controlled by the buoyancy effects and stratification of the hot groundwater. Important factors in a free-convection system are the geometry of the stored heat (determined by the aquifer thickness and well configuration), the permeability of the aquifer, and the temperature difference, i.e. the difference between the initial aquifer temperature and that of the injected and stored heat.

Therefore, to better determine the effects of free convection on the storage efficiency, the decision was made to carry out a series of numerical simulations. These simulations were performed with the computer code HstWin-2D, a code specially developed for heat and solute transport in porous media. The code takes into account the dependency of fluid properties such as viscosity and density on temperature and concentration changes.

5.2.2 Conceptual Model of Storage and Reservoir

The total number of doublets (a storage well and a return well) is dependent on the maximum needed thermal power and energy balance. A typical well configuration for heat storage is shown in Figure 54.

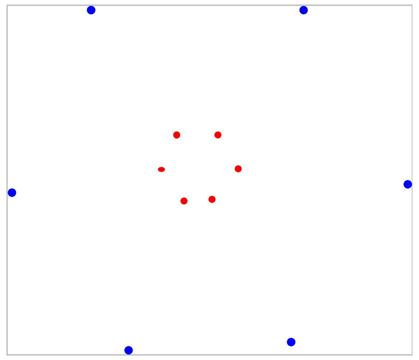


Figure 54 Schematics of a well configuration (red = storage wells, blue= return wells)

From Figure 54 it can be seen that the thermal effects will be radially symmetric. Therefore, for the initial simulations a 2D vertical radial model was constructed. In a radially symmetric model a vertical surface of a cylinder is modeled (see Figure 55). This modeled surface is assumed to be representative of the entire cylinder. This figure shows injection of hot water in an ATES system during the heating season, i.e. the injected water is warmer than the far field temperature.

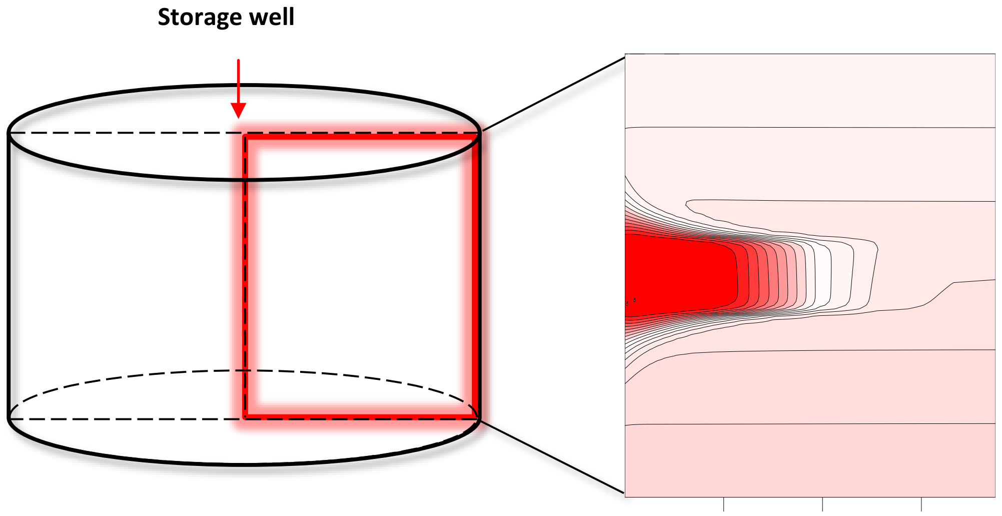


Figure 55 Radial symmetrical model (cooling cycle)

5.2.3 Base Scenario

The parameters shown in Table 18 were used for base-reference scenario and were chosen as representative of a *typical* heat storage installation and respective underground conditions in the UK.

Table 18 Base Scenario Parameters

Storage aquifer	
Aquifer thickness:	100 m
Homogeneous properties	
Isotropic Permeability	kh/kv=1
Permeability	kh = 5Darcy
Porosity	20%
Initial undisturbed temp	20°C
Average aquifer depth	450 metres below ground level (mbgl)
Storage characteristics	
Storage size:	1.7 MW
Well rate (injection/abstraction)	36 m3/h (10 l/s)
Injection temperature	120°C
Annual Injection/ Abstraction Cycles	3 months heat storage *3 months rest period* 3 months heat abstraction *3 months rest period*

Additional information regarding the model set up, are as follows:

- 2D radial symmetry so as to simplify the model for a number of iterations
- Only 1 storage well was modelled
- Any effects of return well injection are neglected, i.e. no thermal interference is assumed to occur as the wells are spaced adequately

The Initial conditions (day 1) were assumed as follows

- Hydrostatic groundwater
- Thermal gradient (2°C/100m) with an average consequent aquifer temperature of 20°C

The following boundary conditions were also considered:

- Upper: constant (T), no flow - impermeable
- Lower: constant (T), no flow - impermeable
- Far field aquifer condition: hydrostatic
- Therefore heat conduction only through the boundary conditions

5.2.4 Homogeneous Simulation Overview

As discussed free convection is expected to be the controlling heat transfer process. Therefore, for the sensitivity runs the following parameters were varied to assess the relative sensitivity and impact:

- Aquifer thickness
- Anisotropy ratio (kh/kv)
- Permeability
- Porosity
- Injection temperature (to investigate the effects of temperature difference between initial aquifer temperature and injection temperature)

Storage and extraction cycles were modelled for a total of 5 years.

Table 19 provides an overview of the simulations and the parameters used

Table 19 List of Simulation Completed

Run	Ratio (kh/kv)	Thickness (m)	Permeability (D)	Porosity (%)	Injection Temp (C)	Parameter Variation
1	**1**	**100**	**5**	**20**	**120**	**base case**
2	2	100	5	20	120	anisotropy
3	10	100	5	20	120	anisotropy
4	1	**50**	5	20	120	thickness
5	1	**200**	5	20	120	thickness
6	1	100	**1**	20	120	permeability
7	1	100	**0.1**	20	120	permeability
8	1	100	5	**10**	120	porosity
9	1	100	5	**30**	120	porosity
10	1	100	5	20	**50**	injection temp

5.2.5 Results of Homogeneous Aquifer Analysis

Temperature evolution in the well during storage and extraction

The following sections and graphs show the effect of the temperature evolution on the storage well due to changes in parameter.

Anisotropy

Anisotropy is the ratio between the horizontal and the vertical aquifer permeability. Free convection (and therefore heat losses) will be suppressed by a lower vertical permeability (higher anisotropy). Figure 56 shows that an aquifer with higher anisotropy factor will favour higher temperatures during the heat abstraction period and improve the storage efficiency.

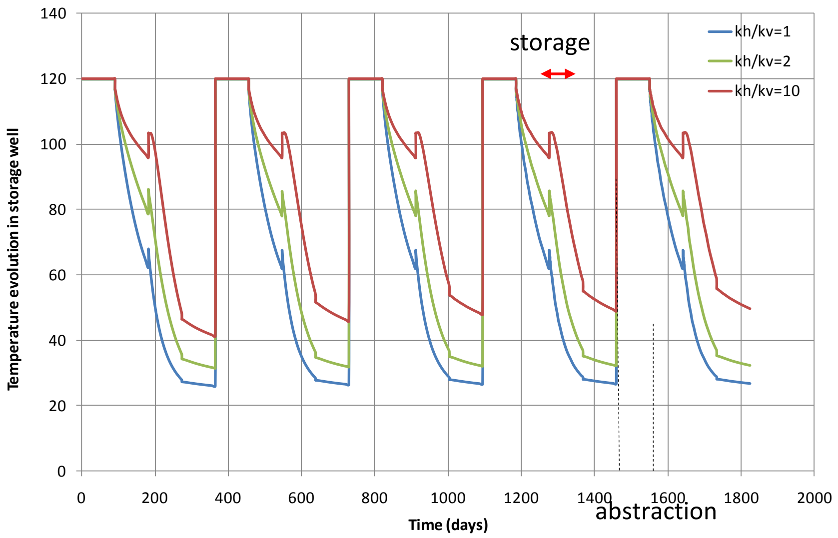


Figure 56 Effects of aquifer anisotropy

Aquifer Thickness

Storage in a thin reservoir limits heat losses due to free convection. This can be seen in Figure 57 which shows that the thicker the reservoir is, the lower the recovered temperature.

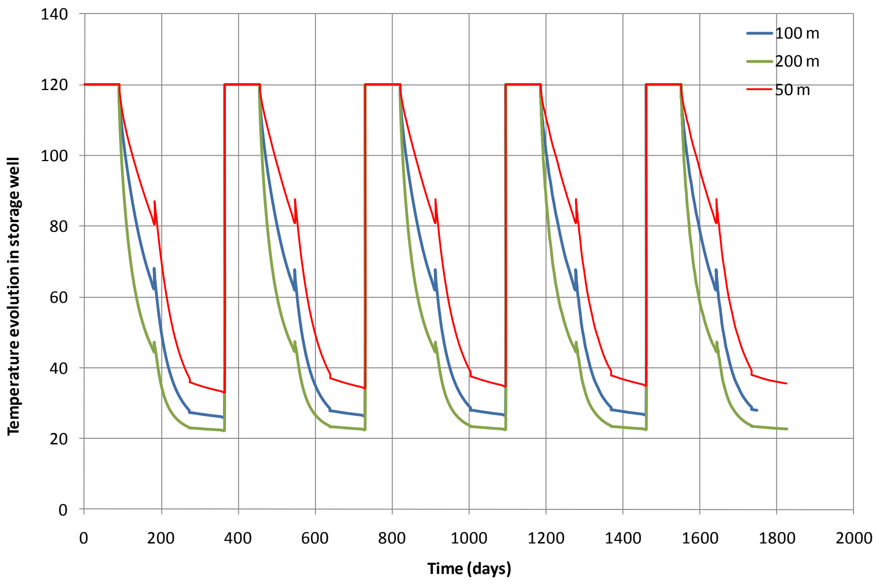


Figure 57 Effects of aquifer thickness

Figure 58 also shows that a lower permeability will favour higher recovery temperatures. For these runs the aquifer is assumed isotropic, i.e. equal horizontal and vertical permeability.

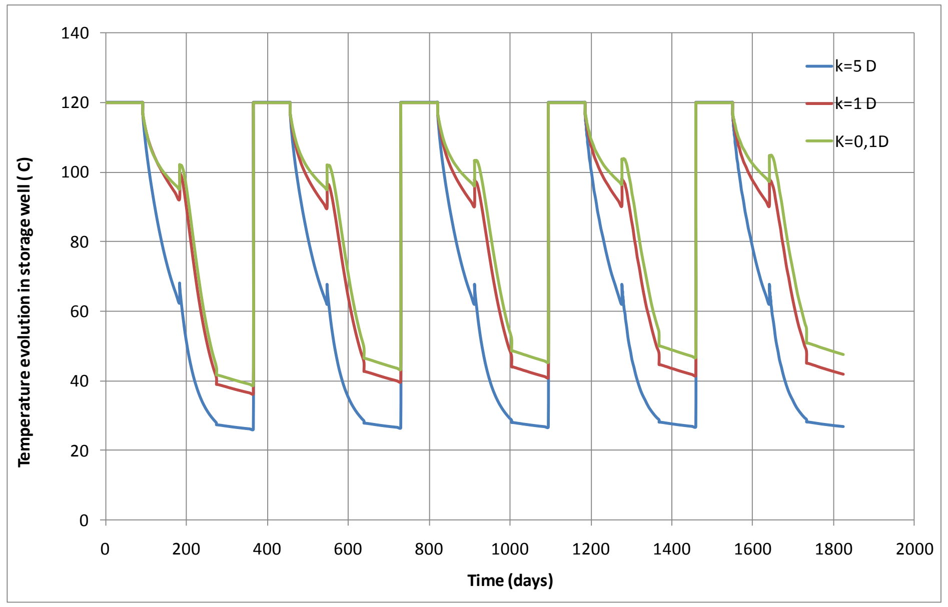


Figure 58 Effects of aquifer permeability (isotropic aquifer assumed).

Figure 59 shows that changes in porosity will have a limited impact in the recovery temperature. Porosity will affect heat transfer effects such as heat conduction and retardation but will not impact the free convection processes.

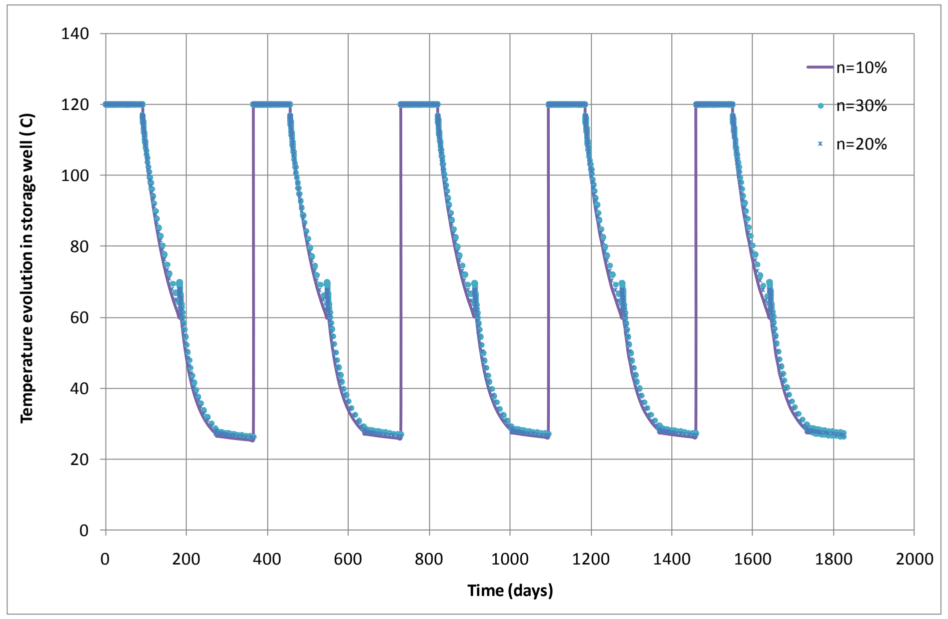


Figure 59 Porosity effects

These sensitivity runs were carried out to determine the impact of the temperature difference (between aquifer temperature and injection temperature) on the storage efficiency. Figure 60 shows that a lower ΔT limits the temperature drop in the well and therefore the return temperatures will stay closer to the injection temperature and will result in a higher recovery efficiency.

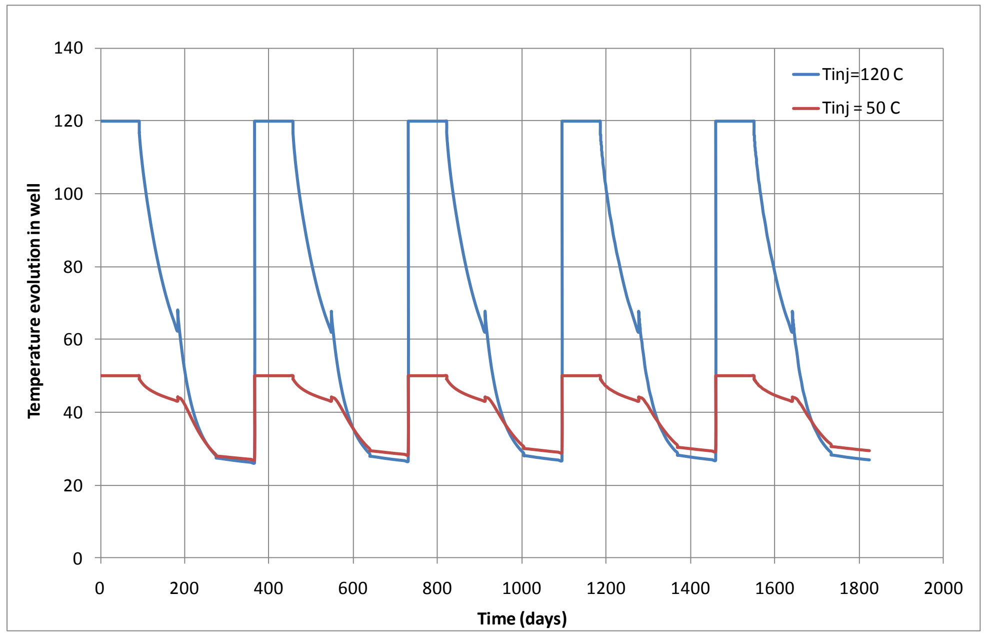


Figure 60 Effects of injection temperature

Recovery efficiency

The recovery efficiency (stored/abstracted) reached steady state during year 4, for each sensitivity run. From Table 20 it can be seen that there are no direct correlations between the effects of changes in individual parameters and storage efficiency.

Table 20 Calculated storage efficiency

Run	Storage efficiency (%)	Rayleigh number (-)
1	25	120
2	40	60
3	60	12
4	40	60
5	10	240
6	58	13
7	57	5
8	24	120
9	26	120
10	55	26

In Figure 61 the storage efficiency results are plotted versus the Rayleigh number. The Rayleigh criterion is used to determine if a system is dominated by free convection (buoyancy flow) or by conduction and is defined as:

$$Ra_x = Gr_x Pr = \frac{g\beta}{\upsilon\alpha} = (T_s - T_\infty)x^3$$

Where:

- x = depth
- Rax = Rayleigh number at x
- Grx = Grashof number at x
- Pr = Prandtl number
- g = gravitational acceleration
- Ts = Surface temperature (temperature of the wall)
- T∞ = Quiescent temperature (fluid temperature far from the surface of the object)
- ν = Kinematic viscosity
- α = Thermal diffusivity
- β = Thermal expansion coefficient

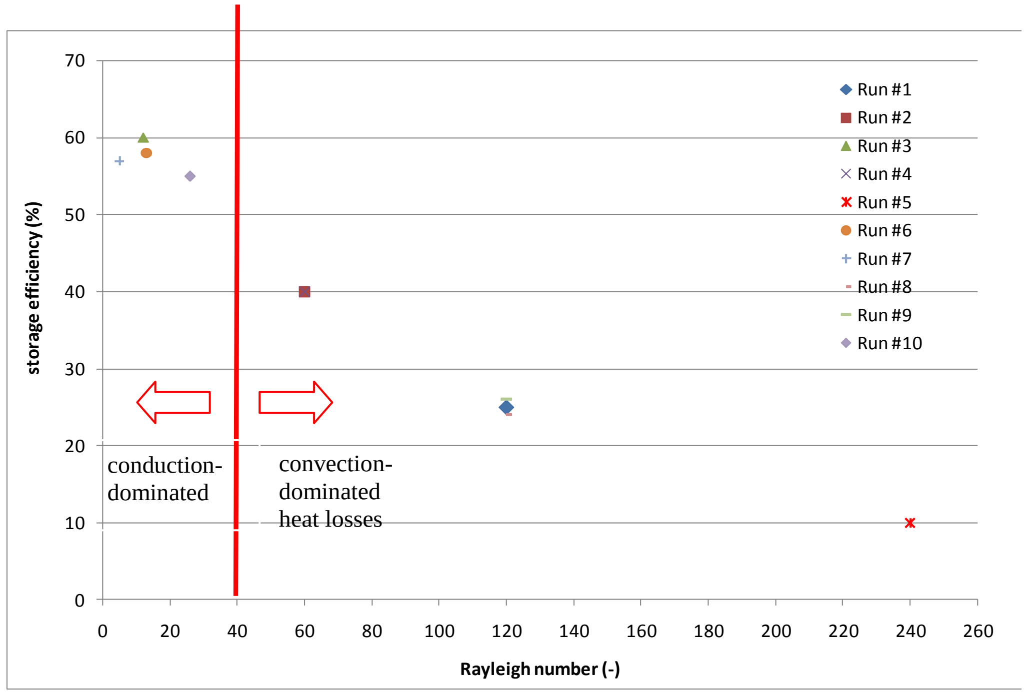


Figure 61 Correlation between the Rayleigh Number and Storage Efficiency

Below a critical number heat transfer will occur mainly by conduction and above it heat transfer will take place by free convection. Some of the parameters previously modelled can influence the Raleigh number and hence it is not possible to identify a fixed threshold for each parameter to ensure an acceptable storage efficiency. Figure 61 shows that above a critical Ra number of approximately 40, heat losses and storage recovery can be correlated exponentially to the Rayleigh number.

5.2.6 Summary and Conclusions

A number of sensitivity runs have been completed to investigate the effect of heat transfer processes on the storage efficiency. From these simulations, free convection accounts for most of the heat losses and subsequent impact on the storage efficiency. Although the conceptual model used is a simplified version of a heat storage facility, the constructed model was useful to assess the effects of the different processes and parameters on the storage efficiency. The main findings are:

1. In a high-temperature heat storage, heat losses will occur mainly due to free convection
2. Therefore free convection is the dominant process affecting the recovery efficiency
3. Results can be correlated with the Ra number which describes the ratio between conduction dominated heat transfer and convection dominated heat transfer.
4. above a critical Ra value of approximately 40 the effects of free convection can be exponentially correlated to the storage efficiency
5. A low Ra number favours a higher storage efficiency

The fact that storage efficiency can be correlated to the Ra number implies that a heat storage project should not be designed based only on individual parameters but according to the combination of key parameters. These are as follows:

1. Aquifer thickness.
2. Aquifer permeability.
3. Temp. difference (between aquifer and storage temperature).

Based on the results and conclusions, the following is suggested to optimize the storage efficiency:

1. Optimise well configuration (distance between storage wells and return wells).
2. Optimise the storage/abstraction strategies.
3. Storage in deeper layers (to reduce the dT of the system) due to the naturally occurring thermal gradient.

5.3 Heterogeneous Aquifer Analysis

In this work a series of models have been developed to explore some of the controls on the storage of heat in subsurface aquifers associated with the injection of hot water during summer season, and the subsequent recovery of this hot water in winter.

Two classes of models are introduced to help inform how the heat injected into the system builds up in a cumulative fashion over several years of injection, and to help inform some of the controls on the recovery temperature of the fluid again modelling this as a function of time.

It is shown that there is a critical balance between (i) the dispersal of heat through the heterogeneity of the rock associated with the shear this introduces into the velocity field, and (ii) the volume of injected fluid during the injection phase. With significant heterogeneities in the system, heat tends to be dispersed further, leading to lower recovery temperatures and heating of a greater volume of rock.

We also provide a brief insight into the possible role of heterogeneities on the dispersal of the thermal front owing to the role of buoyancy, as may arise in more permeable systems.

In a multilayered rock, on the mesoscale, the effect of these heterogeneities is to disperse the thermal front at different rates in the different layers. The well temperature is then given by the average of the flow rates and the temperature of these different streams.

It has also been demonstrated that buoyancy effects may be important in a large layered system; when the density difference associated with the hot and cold fluids acts in tandem with an applied pressure gradient to drive the hot fluid into the reservoir, the flow pattern leads to preferential flooding of the upper parts of the system. However, on subsequent production from the reservoir the buoyancy and pressure forces lead to a different vertical flow pattern. This leads to more rapid production from the base of the reservoir, and breakthrough of cold water before all the original hot injectate has been produced. Again, this reduces the effectiveness of the system, since hot water storage depends on the temperature of the recovered water as well as the ability to recover the heat.

5.4 Numerical Modelling using FEFlow

5.4.1 Overview

A flow transport numerical model was established to assess the potential of a geological system to store heat in the order of 25-50MW depending on the ΔT achieved at a certain point in the cycle. A well field configuration of 50 wells was chosen. Within the well field, 25 wells are arranged in a circular area representing the area of the heat reservoir. The remaining 25 wells (return wells) are arranged within a ring surrounding the heat storage volume. A well abstraction and injection rate of 10l/s was chosen from and to a stratum representing a sandstone aquifer 100m in thickness. The aquifer is over and underlain by strata with comparatively low hydraulic and thermal conductivity. A plan view of the model is shown in Figure 62and 3D model in Figure 63.

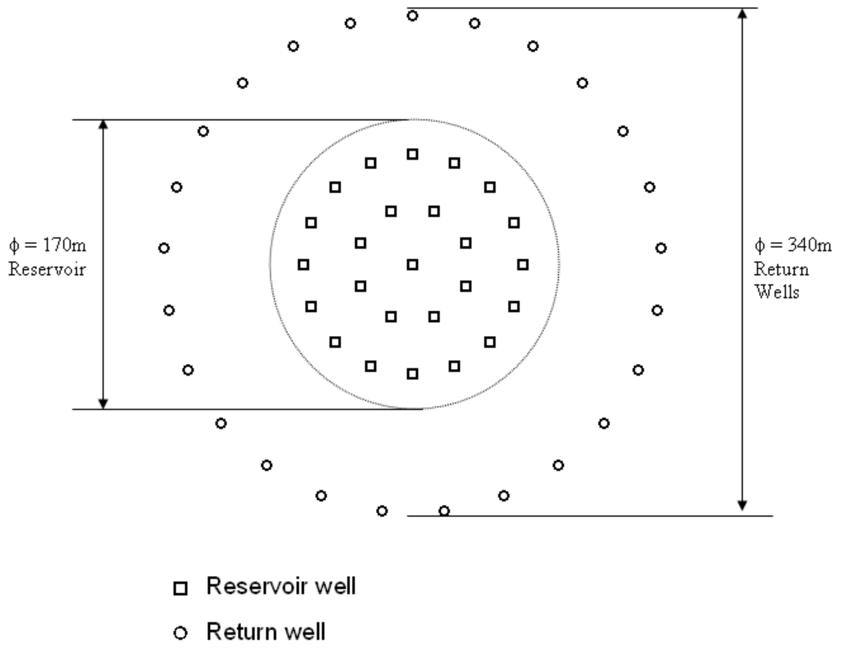


Figure 62: Well field comprising of 50 wells

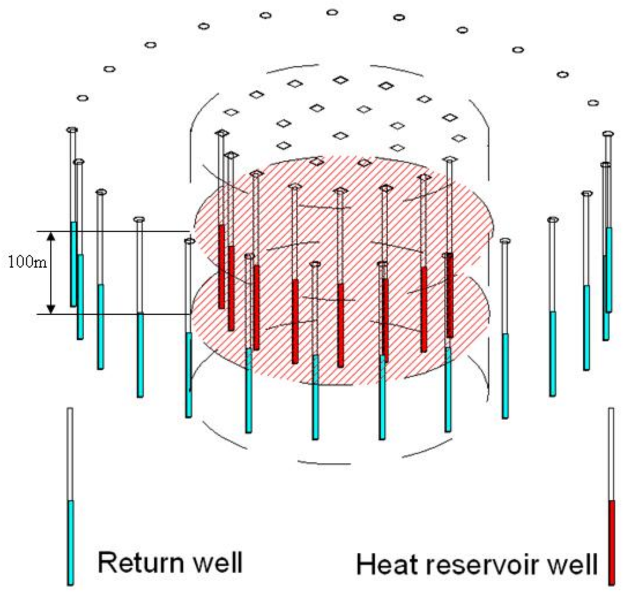


Figure 63: Well field comprising of 25 reservoir and 25 return wells (3D view)

5.4.2 Methodology

For the modelling exercise the Finite Element Subsurface Flow system (FEFLOW) computer program version 5.4 was utilised. FEFLOW is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media. The program uses finite element analysis to solve the groundwater flow equation. The modelling problem was set up for saturated conditions taking into account the temperature dependency of both fluid viscosity and fluid density.

5.4.3 Conceptual Model and Parameters

A summary of the assumed conceptual model including model input parameters entered into the computer program is Figure 64 and Table 21.

Parameters selected on the basis of literature review and initial numerical modelling completed in IWP2.1 with some minor variations to reflect more realistic conditions. The conceptual geological model was also the same as that used in IWP2.1.

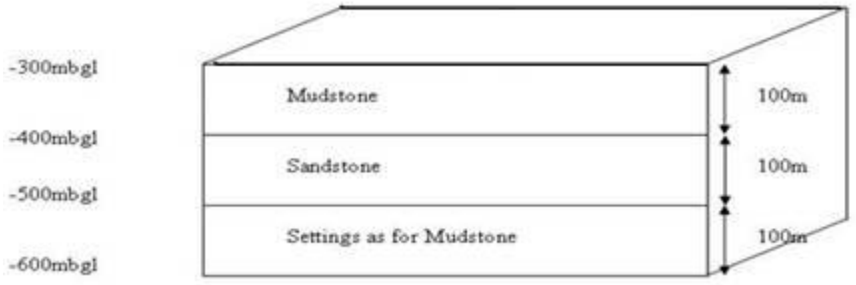


Figure 64 Conceptual model illustrating a sandstone aquifer over and underlain by strata of lower hydraulic and thermal conductivity

Table 21 Key model input parameters

	Aquifer (Sandstone)	**Over and Underlying Aquitard**
Thickness	100m	100m
Flow specific		
Reference hydraulic conductivity (@20°C) **- horizontal** **- vertical**	5×10^{-5} m/s 2.5×10^{-5} m/s	5×10^{-7} m/s 5×10^{-7} m/s
Specific storage (storage compressibility)	0.0001	-
Hydraulic gradient	1/500 (set up via constant head boundaries)	-
Heat transport specific		
Initial temperature	20°C	20°C
Thermal conductivity	2.3 W/mK	1.9 W/mK
Volumetric heat capacity (sandstone)	2.05 MJ/m3/K	2.25 MJ/m3/K
Porosity	20%	-
Heat boundary conditions		
Model top at 300mbgl.	-	17°C (constant heat boundary)
Inflowing lateral water flow	20°C (constant heat boundary)	-
Model bottom at 600mbgl.	-	50mW/m2 (heat flux)
Reservoir wells	120°C	-
Return (outer ring) wells	55°C	-

5.4.4 Results

This section considers the results for the following aspects:

1. Hydraulic head
2. Initial heat distribution
3. Heat trends over a 8 year time period
4. Heat reservoir conditioning and trends of recovery efficiency

Hydraulic Head

The model was set up to run for eight cycles with each cycle representing a period of 5 months constant heat injection, followed by a 7 month abstraction period. As expected, with rising aquifer water temperatures there is a corresponding decrease of dynamic viscosity and an associated increase in hydraulic conductivity. This is reflected by a reduction of hydraulic heads at locations and times of head injection, see Figure 65. This figure shows just over 2 years of cycling.

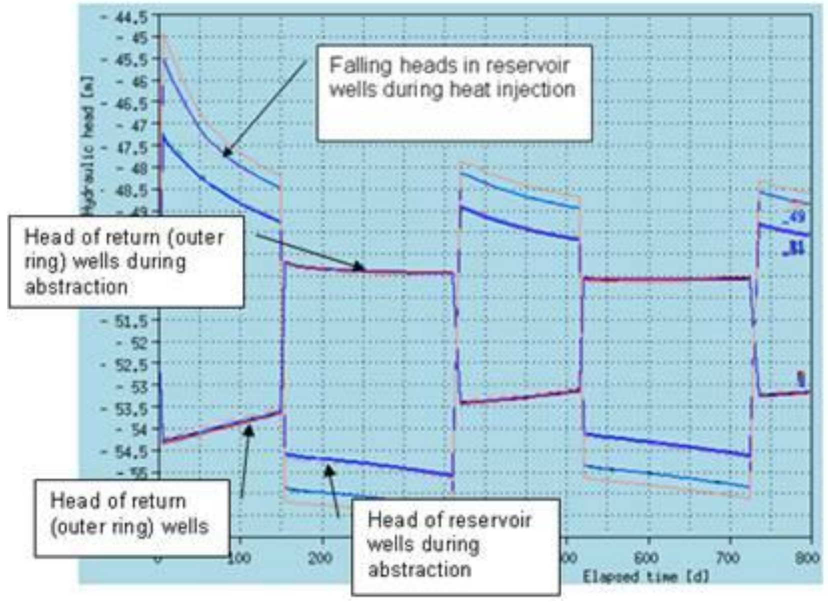


Figure 65 Hydraulic injection and abstraction heads

Initial heat distribution

During the 5 months constant heat injection period, each of the 25 reservoir wells were set to inject water at 120°C at a rate of 10l/s over a time period of 5 months. The distribution of heat within the reservoir prior to and after the first heat injection period has been simulated and is illustrated in Figure 66 and Figure 67.

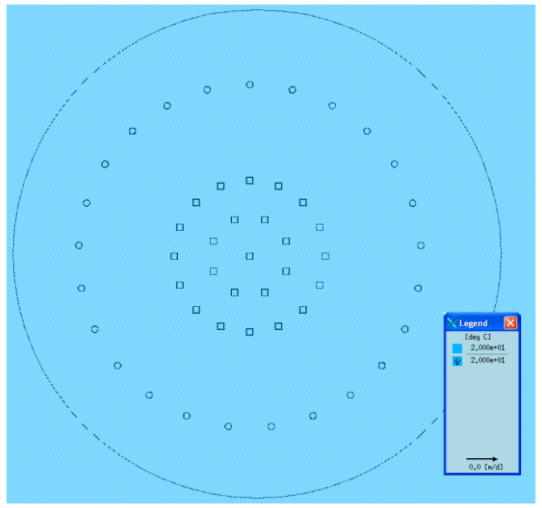


Figure 66 Thermal plot showing the distribution of heat prior to the first (1st year) heat injection period

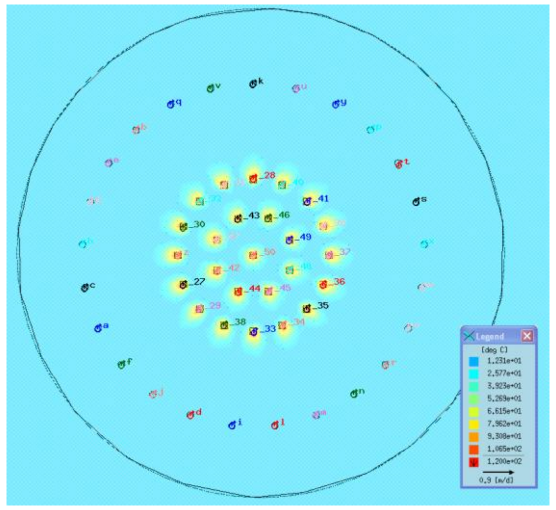


Figure 67 Thermal plot showing the distribution of heat prior after the first heat injection period

Heat trends over a 8 year time period

The program was then further set up to reverse flow at the end of the heat reservoir injection period, i.e. hot water is now abstracted from the heat reservoir and returned to the outer ring wells at a temperature of 55°C. This temperature was chosen as potential return temperature from the district heating network. Injecting water back at temperatures of 55°C via the outer ring wells lowers the temperature gradient and helps to provide a *heat curtain*, thereby reducing heat losses from the central heat storage reservoir. Simulations of trends of reservoir and return well average temperatures for 8 cycles (8 years) are shown in Figure 68. This indicates that a number of wells deliver water with a lower than average temperature, i.e. the abstraction temperature is not constant. This is likely to be associated with an overlap of water flow paths and suggests there is scope for improvement by re-arranging wells within the well-field or optimising the abstraction and injection strategy from individual wells.

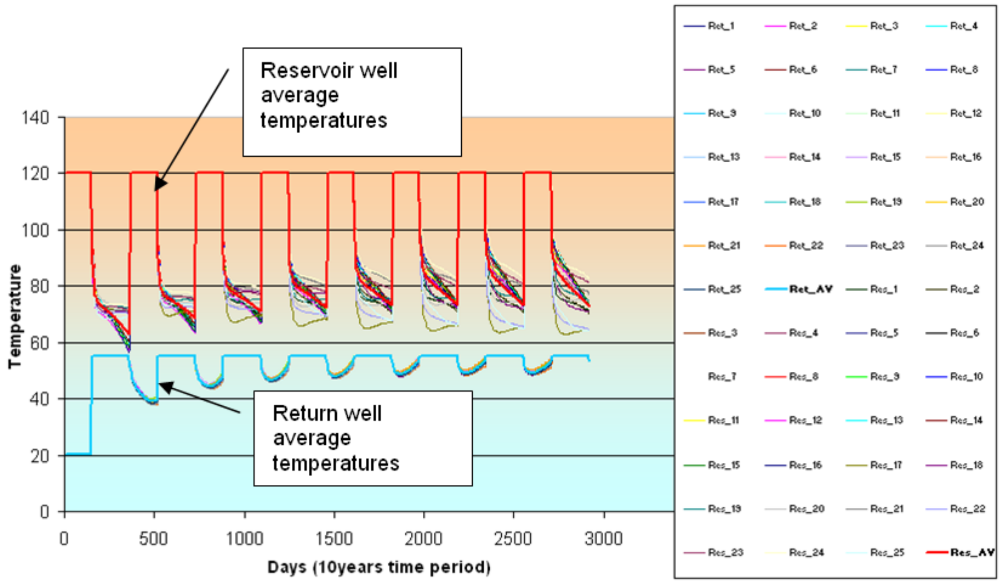


Figure 68 Trends of reservoir and return well temperatures

Heat reservoir conditioning and trends of recovery efficiency

To calculate the storage efficiency over a series of cycles the average temperature differential during each period has been used. By then using a basic energy equation it is possible to consider the average heat rate possible during the heat production and injection phases, see Figure 69.

For the purpose of this initial exercise flow rates and volumetric heat capacity of water have been assumed constant. This graph firstly shows how the possible heat injection rate reduces over time as the return temperature increases in the outer wells. Secondly the heat abstraction rate increases as the heat losses reduce with each cycle.

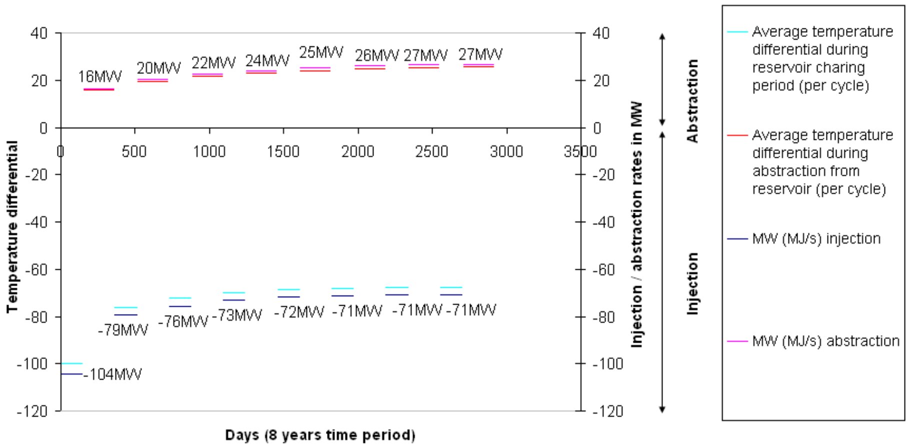


Figure 69 Trends of temperature differentials and energy injection/abstraction rates

The data illustrated in Figure 70 has been created by multiplying of energy rates with the durations of injection (5m) and abstraction (7m). Also shown in this figure are the efficiencies (as percentages) based on the heat energy injected/abstracted per cycle.

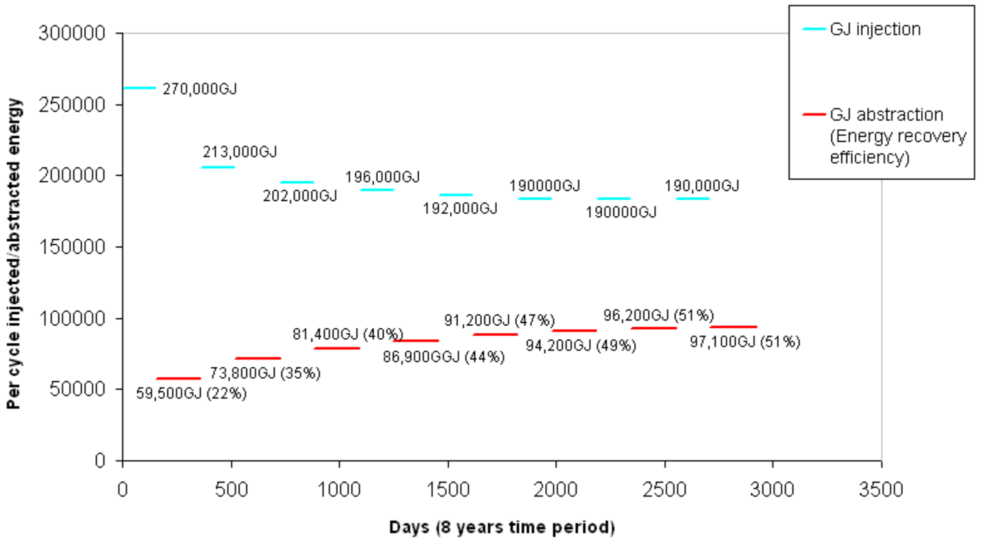


Figure 70 Energy injection/abstraction (recovery efficiency per cycle in %)

Figure 69 and Figure 70 show that high injection rates during the initial cycles will result in relatively low abstraction rates. As a result Figure 70 suggests an energy recovery efficiency of only 22% during the first cycle. However, with time the energy recovery efficiency is indicated to improve reaching an approximate maximum value near 50% after approximately 5 years.

This suggests in order for the system to reach its maximum efficiency a period of conditioning the heat reservoir is required. Figure 71 and Figure 72 represent thermal plots showing the heat distribution prior to and after an eight year heat injection period.

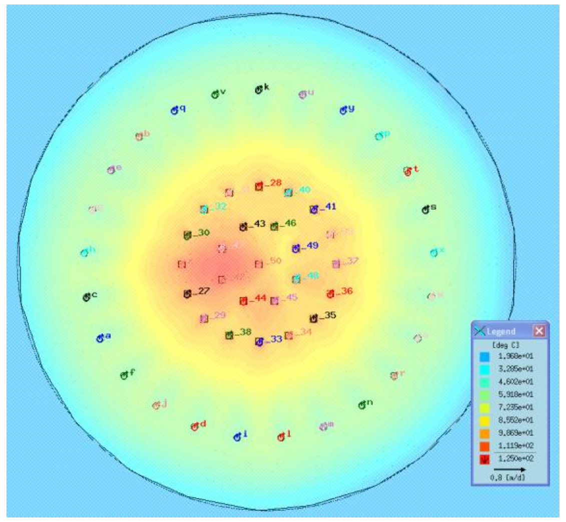


Figure 71 Thermal plot showing the distribution of heat prior to the 8th year of heat injection

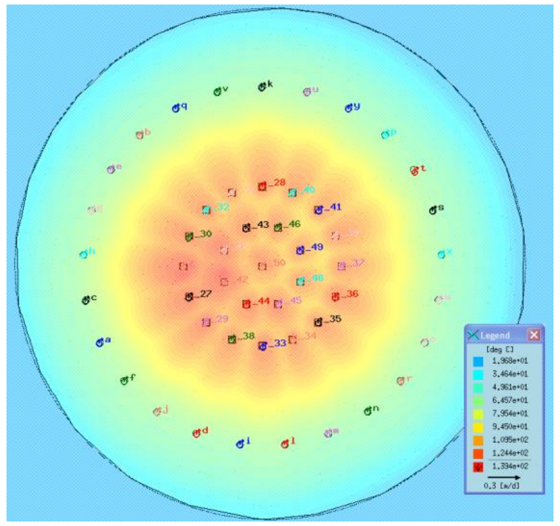


Figure 72 Thermal plot showing the distribution of heat after the 8th year of heat injection

5.4.5 Conclusions and Recommendations

For the heat reservoir to reach its maximum recovery efficiency, a period of conditioning allowing the flow of heat to dissipate within the reservoir area is suggested. For the modelled scenario, this period is shown to be in the order of 5 years. Alternatively, this preconditioning could be accelerated by injecting more heat during the initial injection periods.

This example numerical model indicates that a number of the outer reservoir wells will produce water with a relatively lower than average temperature. This therefore suggests that there is scope for improvement by re-arranging wells within the well-field or optimising flow abstracted/injected from individual wells at different times during the cycle. There is also, the further potential to improve the quality of heat abstraction by configuring each well so as to allow abstraction in focussed depths in the aquifer – this could be attempted by inserting more than one well pump in each well and sequencing pumping accordingly to maximise heat abstraction.

Higher heat recovery efficiencies are achievable where heat abstraction is drawn down to the lowest possible temperature (e.g. 65°C) at the end of the abstraction period. This could be achieved by accepting a lower district heating flow temperature then supplemented by additional heating plant.

The numerical model constructed does not explicitly take into account heterogeneities in the aquifer so this will need to be factored in during the next phase by using a function based upon the analytical modelling. For the hydrogeological conditions considered and with current settings the computer model suggests a recovery efficiency of 50% is feasible. However, optimisations with respect to wells arrangement, flow rate and best possible ratio between energy injection and abstraction may lead to significantly better maximum rates of recovery efficiency, possibly 60-80%.

6 Capital Costing

6.1 Introduction

This chapter covers the design development of the systems up to a point where budget capital costings can be developed. The conveyance of heat from remote large scale power stations is not without precedent in mainland Europe but there are no examples in the UK.

This chapter is split into the following sections

1. Schematics – outline design
2. Capital Costing - Below Ground Installation
3. Complete System Including Primary Heat Distribution Network and Supplementary Plant

As previously discussed there were a number of reasons for discontinuing the further consideration of higher temperature heat storage at 200°C , these are summarised as follows:

1. Practical limits of some of the materials normally used
2. Expense of plant and pipework
3. Unprecedented temperature regime for ground heat storage and associated regulatory concerns
4. Reduction in power station electrical efficiency
5. Environmental risk of storing high temperature and pressure steam
6. No clear benefit for district heating network, i.e. 120 °C is sufficient for flow temperatures of >80 to 85 °C

For these reasons, this section only considers the application of ground heat storage at 35 °C (VLTHW) and 120 °C (MTHW).

6.2 Schematics

Schematic drawings for the VLTHW and MTHW systems are shown in Appendix A, as follows:

- **M100-01 – Indicative Borehole Field Layout** – This drawing sets out a notional requirement for an aquifer thermal energy store (ATES) system, in order to give an idea of the magnitude of storage required
- **M700-01 - Option 1 (Low Temperature) - 35°C - 50km - 250MW** – The system schematic shows the VLTHW being transferred from the power station to the primary energy transfer station, which would be located local to the borefield. Within this station, the VLTHW take off from the power station will be diverted to the ground to be stored, a heat exchanger array will also be provided as a bypass, such that under peak heat take off, the temperature of the transfer fluid can be regulated.

  From the Primary energy transfer station the VLTHW water is then distributed to the transmission network (at a slightly lower temperature than that of the take off due to the inefficiencies when transferring heat).

  Located on the transmission network is a repeater pump station, which would be required to ensure the delivery of the fluid along a long distance.

  The transmission network then enters the district side energy transfer station where the VLTHW will enter the heat pumps, which through use of the refrigeration cycle, will boost the temperature of the water to the optimum distribution temperature of 80-85°C (common UK LTHW temperatures)

  Peak load plant with a diurnal store has also been indicated in order to meet peak load conditions.
- **M700-02 - Option 2 - 120°C - 50km - 250MW -** The system schematic shows the MTHW being transferred from the power station to the primary energy transfer station, which would be located local to the wellfield. Within this station, the MTHW take off from the power station will be diverted to the ground to be stored, a heat exchanger array will also be provided as a bypass, such that under peak heat take off, the temperature can be regulated.

  From the primary energy transfer station the MTHW water is then distributed to the transmission network (at a slightly lower temperature than that of the take off due to the inefficiencies when transferring heat).

  Located on the transmission network is a repeater pump station, which would be required to ensure the delivery of the fluid along a long distance.

  The transmission network then enters the district side energy transfer station where the MTHW will enter a further heat exchanger array which is required in order to provide hydraulic separation between the transmission and distribution networks.

  Peak load plant with a diurnal store has also been indicated in order to meet peak load conditions.

6.3 Budget Capital Costing - Below Ground Installation

6.3.1 Introduction

Capital cost estimates were developed for large scale borehole thermal energy storage (BTES) and ATES systems. These storage systems can be used in a modular way when larger storage capacities are required. A module storage capacity of 5MW was used for the BTES system and 25 MW for the ATES system. This is based on the experience that there is no economy of scale cost impact for BTES heat storage systems beyond 2-3 MWs storage capacity and similarly for ATES heat storage systems beyond ~20 MW storage capacity.

The VLTHW option has a storage temperature in the range of 30-40 ºC for both BTES and ATES. The MTHW option has a storage temperature in the range of 90-100 ºC for BTES and 100-120 ºC for ATES. The lower storage temperature for the BTES system is due to the fact that the BTES system is storing heat starting from close to the ground surface, which does not allow for storage temperatures beyond 100 °C.

6.3.2 BTES System

System Assumptions and System Sizing

The outline sizing of the LT and MT BTES systems is given in Table 22. The major assumptions made, are:

- ΔT during charging 10 ºC for the LT option and 20 ºC for the MT option.
- Specific capacity VLTHW option 40 W/m and for the MTHW option 20 W/m (to maximize the temperature from the borehole field during discharge).
- No casing required for drilling the boreholes. This implies no transition from “soft soil” (e.g. clay, sand, chalk) to “hard rock” (e.g. well consolidated sandstone, granite) over the drilling depth.
- No thermal insulation at the surface for the LT option.
- No thermal insulation of the field headers and piping, except for the piping connecting the MTHW BTES with the plant room.
- Plant room close to the BTES field (50 m distance).

Table 22 Outline sizing BTES systems

Borehole depth (m)	**50**	**100**	**200**
VLTHW option			
Total flow rate borehole field (m³/h)	430	430	430
Heat transfer fluid	water	water	water
Total drilling length (km)	125	125	125
No of boreholes (-)	2,500	1,250	625
No of boreholes in series (-)	4	2	1
Borehole distance (m)	2.5	2.5	2.5
Piping material	HDPE steel	HDPE steel	HDPE steel
Surface area borehole field (1000 m²)	16.3	8.3	4.2
MTHW option			
Total flow rate borehole field (m³/h)	215	215	215
Heat transfer fluid	water	water	water
Total drilling length (km)	125	125	125
No of boreholes (-)	2,500	1,250	625
No of boreholes in series (-)	6	3	2
Borehole distance (m)	2.5	2.5	2.5
Piping material	PEX steel	PEX steel	PEX steel
Surface area borehole field (1000 m²)	17.6	9.2	4.9

BTES system cost estimates

The capital cost estimates for the LT and MT BTES system are given in Figure 73 below.

Not included in these budget cost estimates are:

- cost for land – the cost of land will be mostly dependant on the location of the proposed wellfield
- cost for plant room space – the cost of this is included in the above ground distribution system
- landscaping cost – cost of making good the ground above the wellfield, this is dependent on the standard of landscape to be produced
- permits and licenses – as with the cost for land, the permits and licenses will vary with the local legislation
- taxes – it is unknown currently what taxes would apply to a large scale wellfield installation

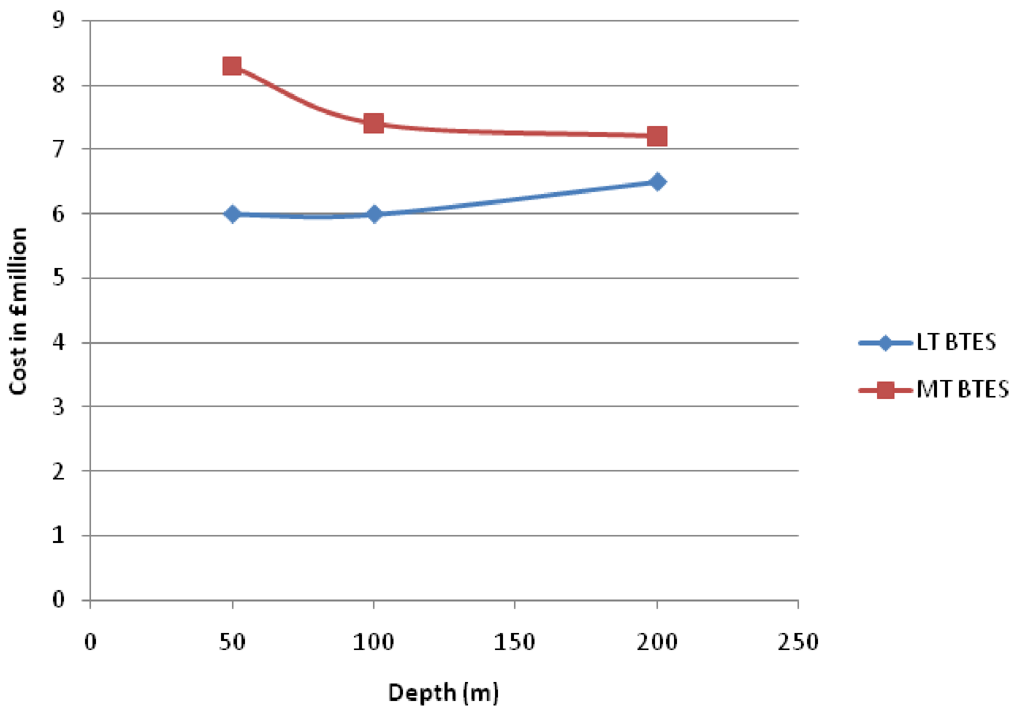


Figure 73 5MW BTES Capital Costs

The capital cost is composed of the main cost items outlined in Table 23 and Table 24.

Table 23 LT BTES Costing Breakdown (%) and Total Cost (£m)

LT BTES	50m	100m	200m
Drilling and borehole completion	76%	81%	85%
Horizontal piping and headers	11%	10%	8%
Plant room M+E and controls	5%	5%	5%
Excavation and insulation	8%	4%	2%
Total cost (million GBP)	*6*	*6*	*6.5*

Table 24 MT BTES Costing Breakdown (%) and Total Cost (£m)

MT BTES	50m	100m	200m
Drilling and borehole completion	63%	74%	85%
Horizontal piping and headers	8%	7%	5%
Plant room M+E and controls	3%	3%	3%
Excavation and insulation	26%	16%	7%
Total cost (million GBP)	*8.3*	*7.4*	*7.2*

It can be concluded that for BTES systems the increase of the drilling cost when drilling deeper boreholes, is compensated by the reduction of the cost for excavation (LT and MT BTES) and top insulation (MT BTES only).

The major operational cost for the BTES system is the electricity cost for the BTES field pumps. For the LT option the pump capacity will be about 60 kWe and for the MT option about 30 kWe.

6.3.3 ATES System

System assumptions and system sizing

The outline sizing of the LT and MT ATES systems is given in

Table 25. The major assumptions made, are:

- ΔT during charging 20 ºC for the LT option and 30 ºC for the MT option.
- Capacity per well, both for production and discharge, 75 m³/h.
- Aquifer thickness about 100 m.
- Drilling method for “soft soil” (e.g. clay, sand, chalk) reverse rotary and for “hard rock” (e.g. well consolidated sandstone, granite) (roto) percussion.
- Circular well configuration: inner circle warmer wells, outer circle colder wells. Distance between inner and outer circle 100m.
- Open hole in aquifer for LT option, screened borehole for MT option.
- No blow out prevention required for drilling.
- No thermal insulation of the field headers and piping for the LT option.
- Water treatment required for MT option only. Assumption: acidization is applied as treatment method.
- Plant room within the inner circle of the ATES field.

Table 25 Outline Sizing for ATES systems

Well depth	**200m**	**400m**	**600m**
LT option			
Total flow rate well field (m³/h)	1,100	1,100	1,100
Total drilling length (km)	6	12	16
Diameter inner circle (m)	140	140	140
Casing and piping material	HDPE, stainless steel	HDPE, stainless steel	HDPE, stainless steel
Number of water wells (-)	30	30	30
MT option			
Total flow rate well field (m³/h)	750	750	750
Total drilling length (km)	4	8	12
Diameter inner circle (m)	140	140	140
Piping material	GRE, stainless steel	GRE, stainless steel	GRE, stainless steel
Number of water wells (-)	10	10	10

ATES system cost estimates

The capital cost estimates for the LT and MT ATES system are given in Figure 74 below.

Not included in these Budget cost estimates are:

- cost for land
- cost for plant room space
- landscaping cost
- permits and licenses
- taxes

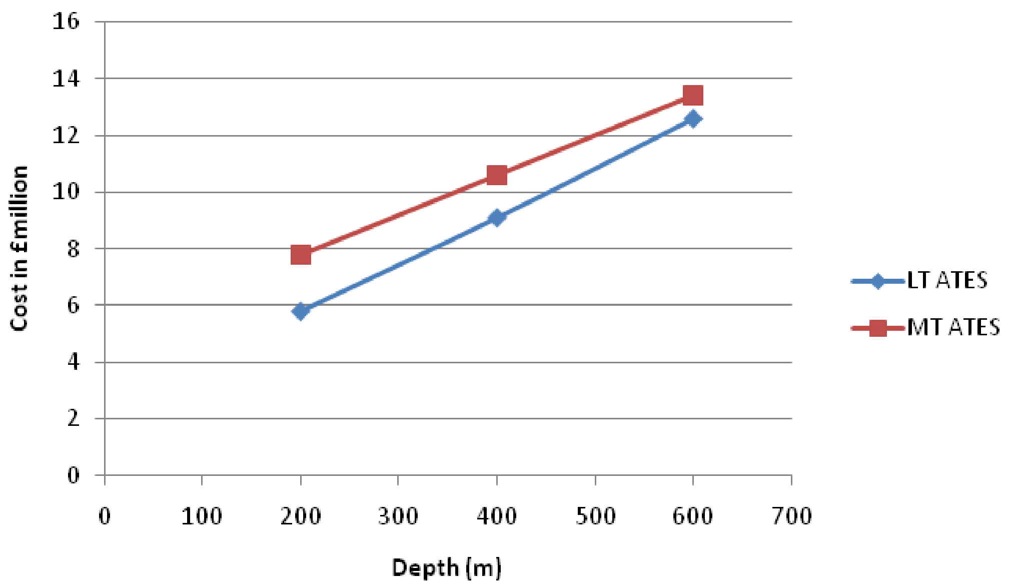


Figure 74 Capital Costing - 25MW ATES (£m)

The capital cost is composed of the main cost items as indicated in Table 26 and Table 27:

Table 26 LT ATES Costing Breakdown (%) and Total Cost (m£)

LT ATES	**200m**	**400m**	**600m**
Drilling and well completion	51%	68%	77%
Well M+E	23%	15%	10%
Field piping and cables	14%	9%	7%
Plant room M+E and controls	12%	8%	6%
Total cost (million GBP)	*5.8*	*9.1*	*12.6*

Table 27 MT ATES Costing Breakdown (%) and Total Cost (m£)

MT ATES	**200m**	**400m**	**600m**
Drilling and well completion	37%	53%	63%
Well M+E	38%	28%	22%
Field piping and cables	11%	8%	7%
Plant room M+E and controls	15%	11%	8%
Total cost (million GBP)	*7.8*	*10.6*	*13.4*

It can be concluded that for ATES systems the increase of the drilling cost when drilling deeper wells, due to different equipment requirements, is the major factor causing the cost increase. The MT option is preferred due to the fact that a higher ΔT during charging is assumed, resulting in a reduction of the number of wells required.

The major operational costs for the ATES system are the electricity cost for the ATES well pumps and the use of chemicals for the water treatment (MT option only). For the LT option the pump capacity will be about 500 kWe and for the MT option about 350 kWe. Treatment with HCl to lower the Ph will cost in the range £0.50-1.00 per MWh thermal energy stored, unless the groundwater has a high alkalinity.

The capital cost for a specific project may show a rather large variation as compared to the cost estimates presented, mainly as a result of variation in the drilling cost. This is not only due to variations in the geological sequence, but to a large extent to the market situation for drilling.

Additional research is required regarding the cost for submersible pumps that are suitable for temperatures in the range 100-120 ºC. y

The options set out in Table 28 have been costed.

Table 28 Capital Costing - Summary of Systems Modelled

Temperature	Capacity	Distance to Secondary Heat Station	Ground System
35ºC	250MW	10km	<200m depth ATES
35ºC	250MW	50km	<200m depth ATES
35ºC	250MW	100km	<200m depth ATES
120ºC	250MW	10km	~400m depth ATES
120ºC	250MW	50km	~400m depth ATES
120ºC	250MW	100km	~400m depth ATES

For the lower temperature, an ATES system of <200m has been considered as the current regulatory controls will possibly allow for such a system in a near surface aquifer. For the medium temperature system an ATES system with a starting depth of 400m is considered.

6.4 Complete System Costing

6.4.1 Sources and notes

The costings have been based on a number sources as follows:

- Discussions with manufacturers
- Previous project quotes / costings
- Experience of the project team
- Prelims (8%), design and legal fees (7%) and project management (5%) have been added to the net cost of each system.

It should be noted at this stage that many of the items required are bespoke due to the large size of the proposed systems. Obtaining more detailed cost estimates should form part of the site specific pilot studies. Examples include:

Pumps – specialist manufacture for the flow rates (up to 3000l/s) and high pressures required (25 bar). District heating pumps of this size are only used in a few large transmission systems in locations such as Copenhagen

Thermal storage – based on insulated steel stores and previous experience in Denmark of building large accumulators

District heating pipework – only a few manufacturers produce pipes up to 1,200mm nominal diameter, anything above this would be bespoke. Pipework is assumed to be direct buried pre-insulated steel pipework throughout. In practice there may be cost reductions by using plastic pipework for the VLTHW system.

Heat pumps – specialist large scale heat pumps using a bespoke configuration of compressor/evaporator rather than a packaged product. Also, heat pumps based on R134a cannot supply heat much beyond 80°C; requiring a butane or other natural refrigerant based system.

Note that VLTHW is used throughout to refer to the heat network system required to distribute the heat from the LT stores. Similarly MTHW is used to refer the heat network system used to distribute heat from the MT stores.

6.4.2 District Heating Pipework

The cost of heat pipework dominates the 50km and 100km schemes as indicated in Figure 74, and is a significant factor in the VLTHW system due to the lower temperature differences across the flow and return. Some pipework is up to 1600mm nominal diameter, for which costs were extrapolated. A comparison of the data is shown in Figure 75. This will be a crucial variable and during the pilot study development a review of the network costs for large diameter pipework (>700mm) and the associated civil works will be required. Some of the network may run in soft ground which has the potential to significantly reduce costs. At present costs are based on the lower of the cost series. This cost data is subject to considerable uncertainty due to the diameter and length of pipework required which is unprecedented in the UK for heat networks.

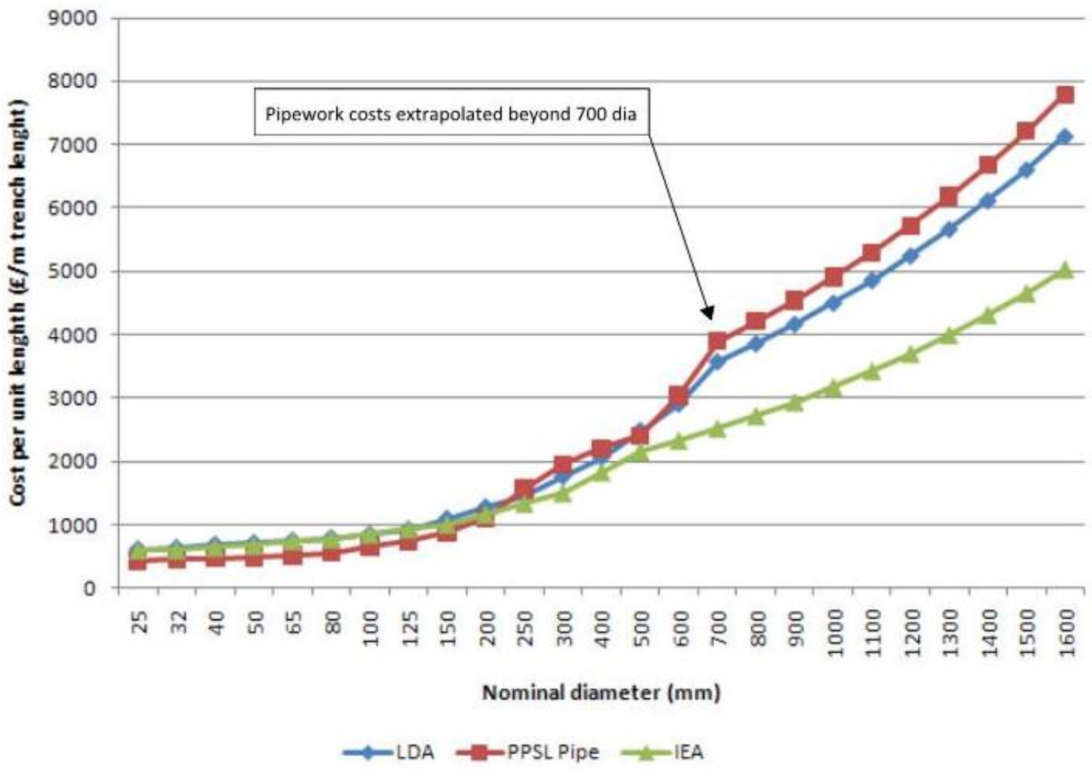


Figure 75 Comparison of three pipe costs sources, extrapolated up to 1600mm

The three sets of figures are produced from :

- Buro Happold data from London Thames Gateway Heat Network project – figures beyond 700mm extrapolated
- Perma-Pipe Services Limited (PPSL) supplied information – figures beyond 700mm extrapolated
- International Energy Agency - District Heat and Cooling Project – Comparison of distributed CHP/DH with large scale CHP/DH, pg 89.

6.4.3 Budget Capital Cost Outputs

Figure 76 and Table 29 give a detailed capital cost breakdown, gross of project management, design fees and prelims for each of the options considered.

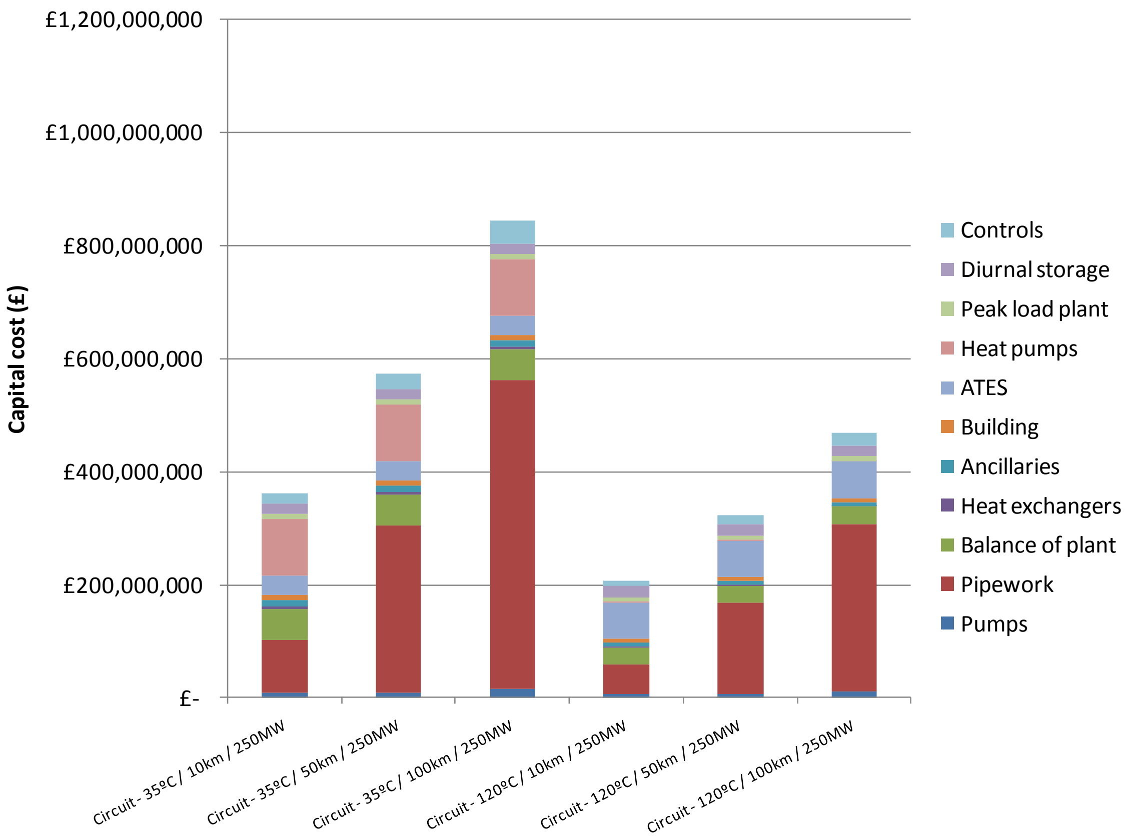


Figure 76 Budget Capital cost breakdown by option

Table 29 Summary of Budget capital cost breakdown

Temp	**LT - 35°C**	**LT - 35°C**	**LT - 35°C**	**MT - 120°C**	**MT - 120°C**	**MT - 120°C**
Distance	10	50	100	10	50	100
Pumps	£7,700,000	£9,700,000	£15,700,000	£6,200,000	£7,400,000	£11,000,000
Pipework	£94,230,000	£295,230,000	£546,480,000	£52,290,000	£160,890,000	£296,640,000
Balance of plant	£55,524,900	£55,524,900	£55,524,900	£30,483,000	£30,483,000	£30,483,000
Heat exchangers	£4,000,000	£4,000,000	£4,000,000	£2,000,000	£2,000,000	£2,000,000
Ancillaries	£10,223,000	£10,223,000	£10,223,000	£6,080,500	£6,080,500	£6,080,500
Building	£9,400,000	£9,400,000	£9,400,000	£7,400,000	£7,400,000	£7,400,000
ATES	£35,610,000	£35,610,000	£35,610,000	£64,410,000	£64,410,000	£64,410,000
Heat pumps	£100,150,000	£100,150,000	£100,150,000	£-	£-	£-
Peak load plant	£7,500,000	£7,500,000	£7,500,000	£7,500,000	£7,500,000	£7,500,000
Diurnal storage	£20,000,000	£20,000,000	£20,000,000	£20,000,000	£20,000,000	£20,000,000
Controls	£17,216,895	£27,366,895	£40,229,395	£9,893,175	£15,383,175	£22,350,675
Sub-total	**£361,554,795**	**£574,704,795**	**£844,817,295**	**£207,756,675**	**£323,046,675**	**£469,364,175**
Pre-lims and profit (8%)	28,924,384	45,976,384	67,585,384	16,620,534	25,843,734	37,549,134
Fees - design and legal fees (7%)	25,308,836	40,229,336	59,137,211	14,542,967	22,613,267	32,855,492
Project management (5%)	18,077,740	28,735,240	42,240,865	10,387,834	16,152,334	23,468,209
TOTAL	**£433,865,754**	**£689,645,754**	**£1,013,780,754**	**£247,808,010**	**£386,156,010**	**£561,737,010**
Cost excluding storage	£343,197,855	£598,977,855	£923,112,855	£114,741,900	£253,089,900	£428,670,900
Cost increase for storage	£90,667,899	£90,667,899	£90,667,899	£134,566,110	£134,566,110	£134,566,110
%	21%	13%	9%	54%	35%	24%

The cost of the ATES storage as a proportion of total project costs varies between around 10% and 50% depending on the distance from the power station to the heat load. The impact on the MT options is much greater due to their lower overall cost and the higher cost of the ATES boreholes.

6.4.4 Cost Curves

Figure 77 and Figure 78 show the cost curves developed for the options.

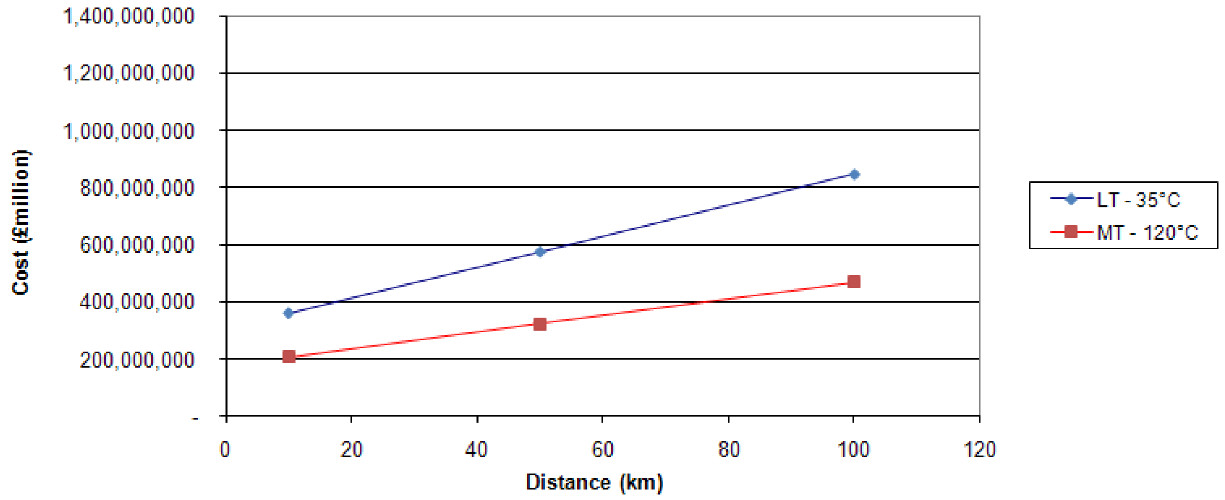


Figure 77 Cost curve comparing total cost versus distance for the options modelled

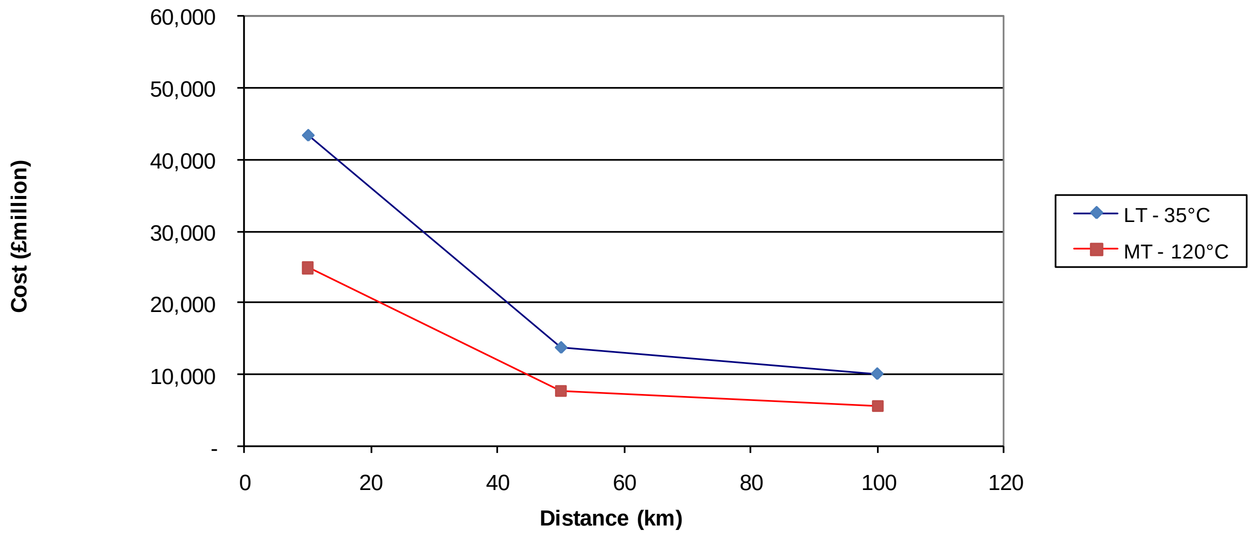


Figure 78 Cost curve comparing cost per km versus distance (km) for the options modelled

Figure 78 shows a sharp drop off in cost/km length, this is due to the fact that for the varying lengths of network, the base plant requirement remains the same as that required for the 10km network. With the key variables on distance being only the length of pipework and additional pumps required. Beyond 50km the heat network cost is around 50% of the total cost and the marginal cost tends towards the marginal cost of extending the heat transmission network. Note this does not imply that there is an optimum level, merely that the most promising pilot locations are likely to be as close as possible to existing heat loads.

The results clearly show that the VLTHW system (35 °C) is significantly more capital intensive than the MTHW system (120 °C) and that this cost difference increases with distance.

The headline values indicated within the table above are :

- Cost of heat pumps and the larger diameter pipework required to accomdate the lower temperature difference is the dominant driver for the higher VLTHW system costs
- The cost of ground storage for the MTHW system is much higher than that for the VLTHW system
- Above 50km pipework costs dominant across both temperature regimes, increasing with the length of network required
- The cost of pumps increases with the network length due to the requirement for larger, more powerful pumps capable of producing the required hydraulic pressure to overcome the network distance

One element which is not included within these cost comparisons is that of the cost to retrofit the steam turbine plant in order to be able to extract heat at 120°C in order to supply the MTHW system. This cost should be further explored within the pilot study development, but is assumed to be included as part of any new build power plant.

7 Economic Modelling, Energy and Carbon Balance

An example operational model and financial assessment of the options developed has been completed. This section summarises the methodology and key findings. A case study of Hartlepool Nuclear Power Station linked to supply heat to Middlesbrough has been chosen as the initial multi-criteria analysis suggested there was a strong potential in this area. The hydrogeology suits medium temperature storage and the Nuclear Power Station has been identified for replacement in recent government publications.

The operational model uses an annual energy balance approach using monthly heating demands, whilst the financial analysis calculates a unit cost of heat over the lifetime of the heat off take scheme.

7.1 Operational modelling

The following approach has been used for the operation model:

A model was produced utilising DECC data as provided by the ETI for energy consumption in Middlesbrough. By applying the degree days data for North East England the space heating demand was then calculated. Domestic hot water demand assumed to be seasonal for purposes of this model.

Heat losses from heat network were added to give gross heat demand – 13% (VLTHW) and 15% (MTHW). No heat loss was assumed from the VLTHW transmission system, the 13% of losses is from the distribution network after the heat pumps/district energy station. These losses were assumed to be constant throughout the year.

The ground storage thermal efficiencies of 85% (VLTHW) and 75% (MTHW) were assumed. These losses were included in the total heat demand. The storage size was determined by calculating the shortfall in heat output from the power station versus the gross heat demand.

The heat off take output (in MW) from the power station was then adjusted such that the following condition was satisfied on an annual basis:

Total heat demand (including store losses) + Heat loss from network = Gross power station heat output

The heat balance for the store was set such that the following condition was satisfied:

Total heat demand from store + heat losses from store = Heat input to store from power station off take

In the VLTHW option zero electrical loss from the power station due to heat off take has been assumed. A heat pump COP of 3.6 has been assumed based on information from chiller company York[13]

A z-factor of 5 has been assumed for heat off take from the power station in the MTHW option. This means for every unit of heat taken from the steam turbine 1/5 units of electricity are lost.

Finally, heat off takes from the steam turbine of 93MW (VLTHW) and 136MW (MTHW) were calculated.

7.2 Heat balances

Monthly and daily energy balances for the VLTHW system are shown in Figure 79 and Figure 80. Note the daily balance shows the average daily load in MW to provide a scale for the plant and equipment. The system is assumed to balance daily load fluctuations (e.g. over the diurnal cycle) by using large thermal stores located at the heat loads. This smooths demand on the power station and enables the diameter of the long distance heat mains to be minimised.

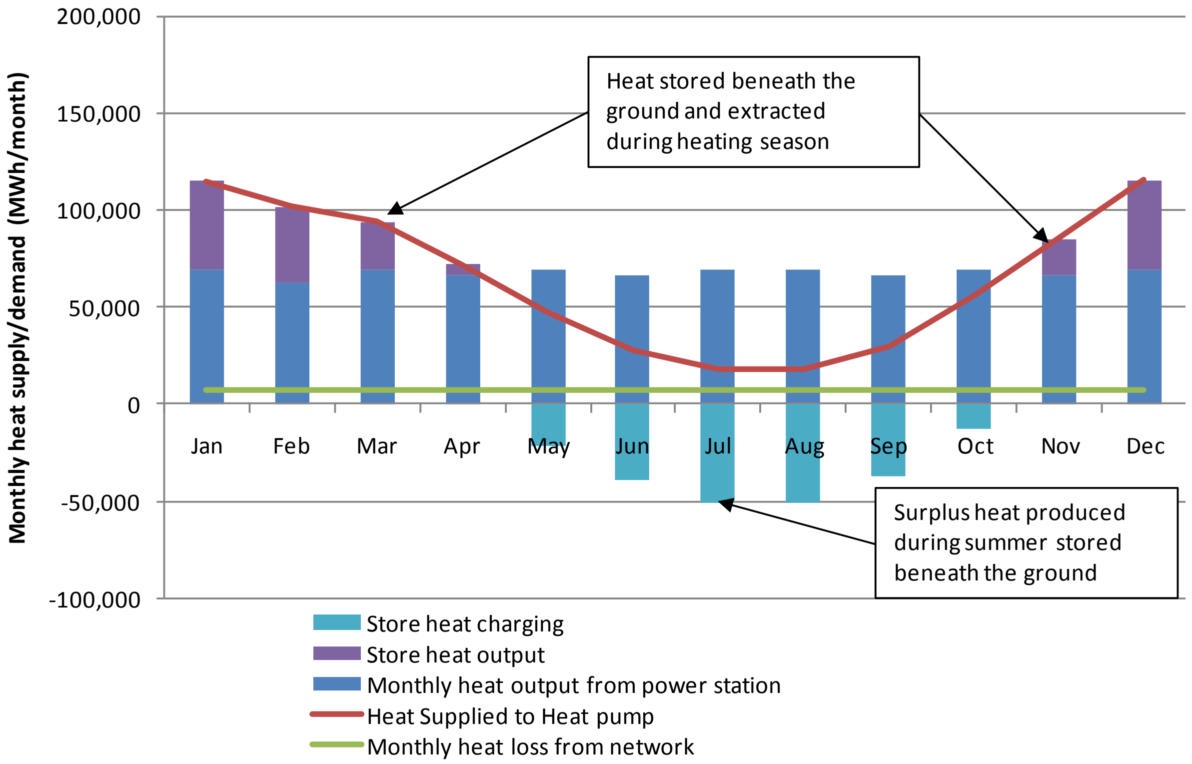


Figure 79 Monthly energy balance for ground storage system (LT system)

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[13] Personal correspondance with York (Johnson Controls) for large scale bespoke heat pumps, supplying up to 80 °C

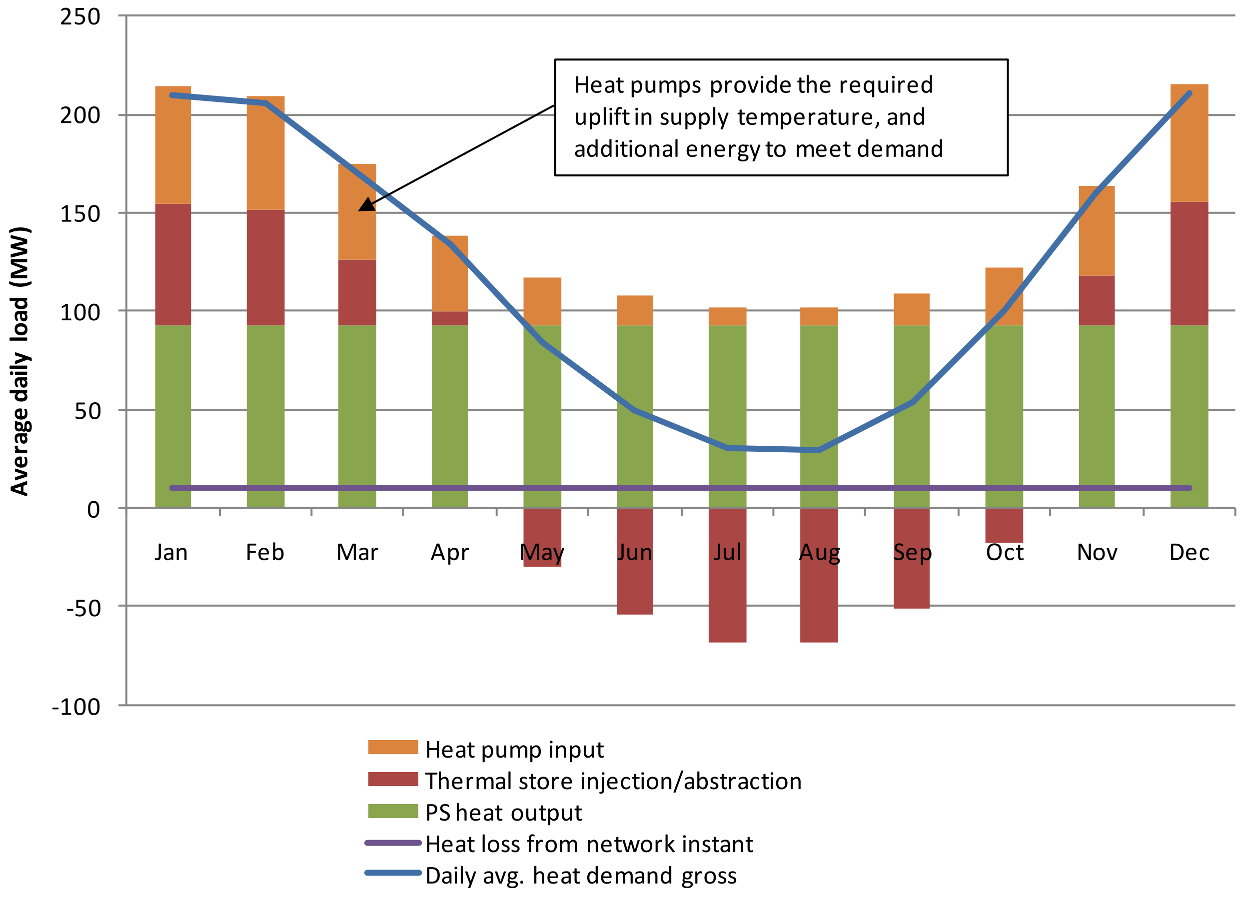

Figure 80 Daily energy balance for ground storage system (LT system)

As shown in Figure 80 heat contributions from the heat pump compressor significantly reduces the heat off take from the power station. Monthly and daily energy balances for the MT system are shown in Figure 81 and Figure 82.

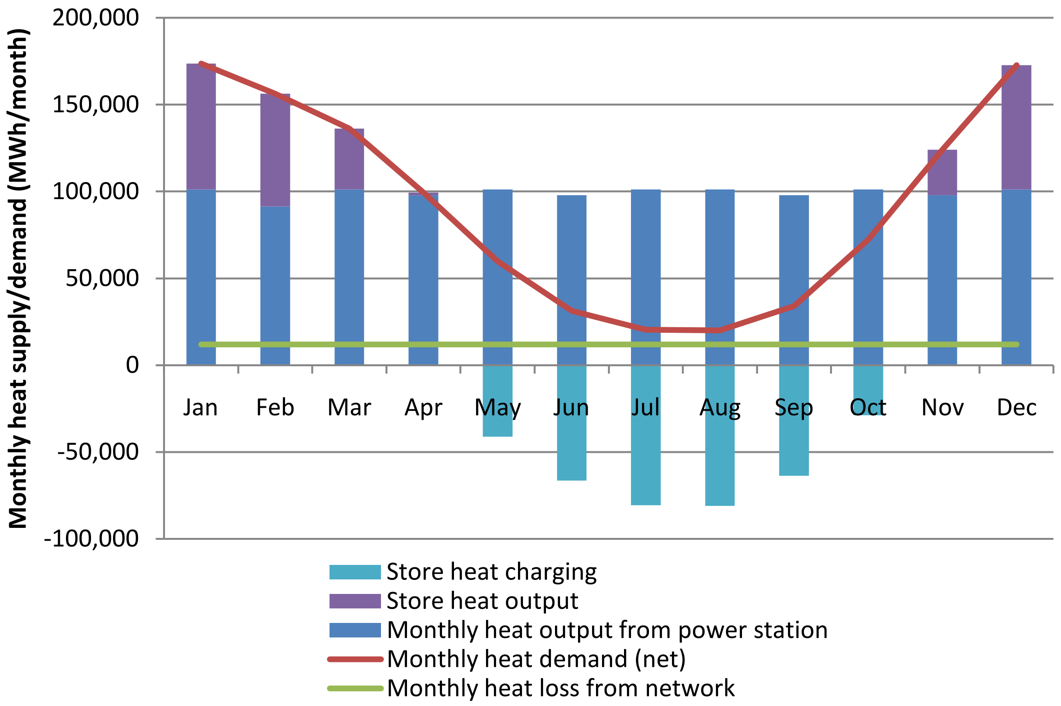

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Figure 81 Monthly energy balance for ground storage system (MT system)

From Figure 81 it is clear that the heat charging in the summer months is significantly higher than the heat output from the thermal store in the winter, due to the 25% heat loss in the store. Also, as the model does not account for the relative ‘base load’ nature of domestic hot water consumption the heat losses from the network outweigh the heat demand during summer months.

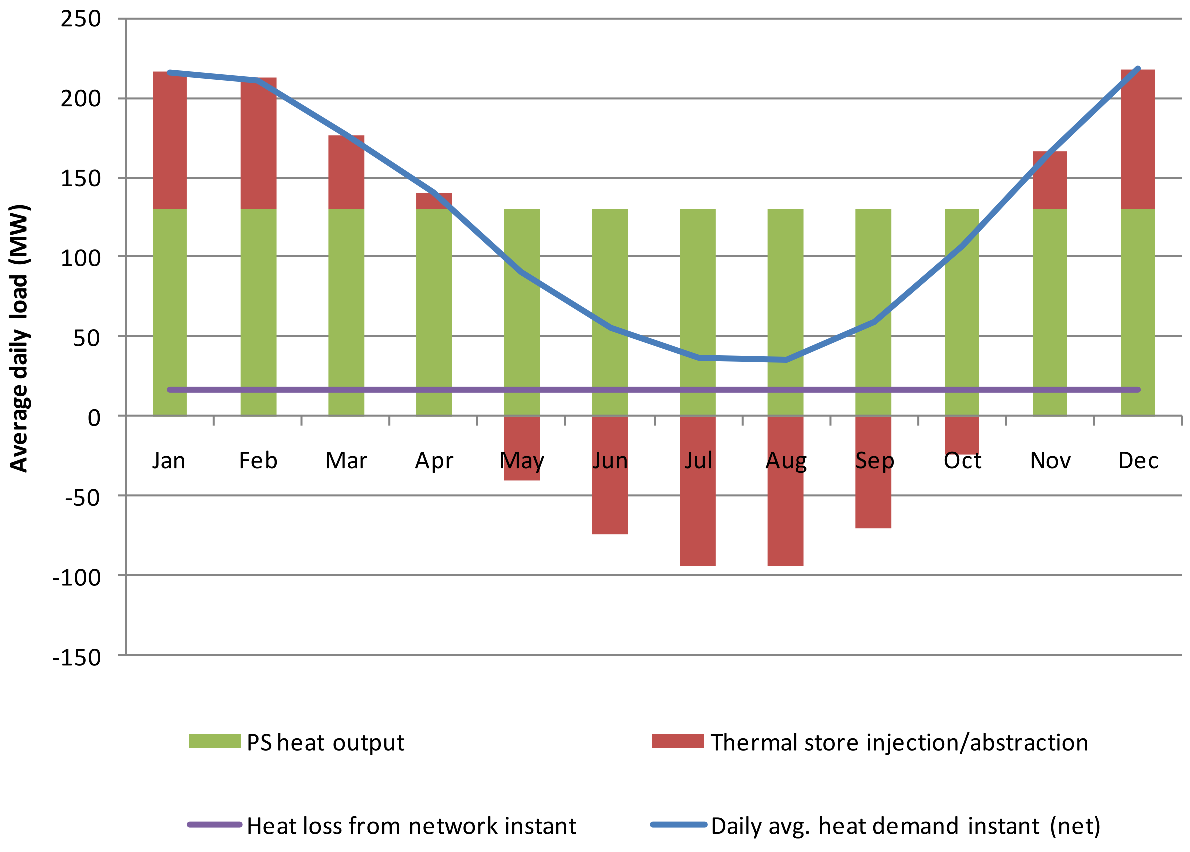

Figure 82 Daily Energy Balance for Ground Storage System (MT system)

Total average daily demand is shown as just under 250MW in Figure 82. This value is set by the demand data for the area selected. Other points of note include that the power station output has to be significantly greater than 50% of the winter peak load in order to provide sufficient charging capacity during the summer months.

7.3 Operational Modelling Results

Table 30 below shows the operational modelling results on an annual basis. Figure 83 shows this graphically for the VLTHW system. As can be seen from the table of results in Table 30 the pumping energy for the VLTHW system is much larger than that for the MTHW system. This is due to the larger flow volumes required due to the smaller temperature differences within the fluid. In practice this energy would be transferred to the heat network, helping to offset heat losses. Further figures of note are the losses through storage, which are considerably larger for the MTHW system.

Table 30 Results from Operational Model

	Units	VLTHW option - 35 °C	MTHW option - 120 °C
Pumping energy - load factor		*53%*	*54%*
Pumping power - total pump rated capacity	MW	29.7	15
Pumping energy	MWh electric	138,734	72,525
Lost electrical output	MWh electric	-	238,114
Heat pump electrical input	MWh electric	265,741	-
Heat demand (net of losses)	MWh	956,666	
Heat supply upto HPs (net)		690,925	-
Heat loss from ground store	MWh	31,809	90,504
Heat loss from network	MWh	89,820	143,500
Heat supply (gross off take from turbine)	MWh	812,490	1,190,572
Heat off take from power station	MW	93	136
Heat storage - recoverable energy	MWh	180,195	271,512
Capacity of heat pumps	MW	60	-

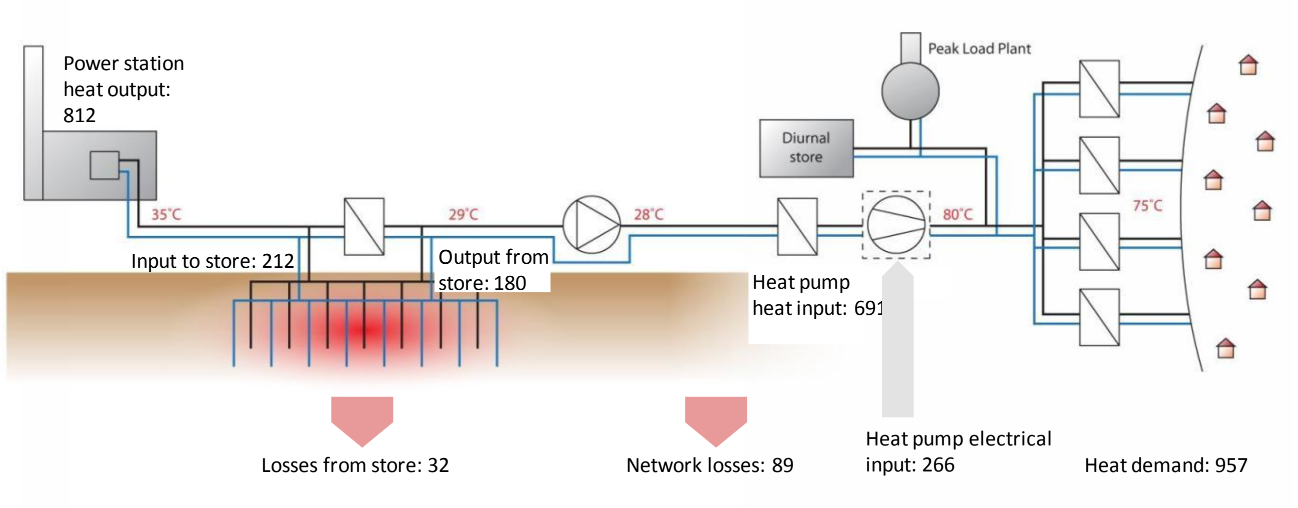

Figure 83 Annual energy flows for VLTHW system (GWh/yr excluding pumping energy)

Table 31 below shows a detailed breakdown of the pumping energy for each of the 50km options, which has been included in Table 30 also.

Legend :

PETS – Primary energy transfer station

DETS – District energy transfer station

Table 31 Schedule of pumps and capacities

Circuit	Plant space	Pumpset	Duty pumps	Duty (l/s)	Head (kPa)	Motor size assumed (MW/pump)*
LT - 35°C - 50km	Power plant	Primary	1	1667	700	1.46
LT - 35°C - 50km	PETS	Circulation - borefeld	1	1667	1000	2.08
LT - 35°C - 50km	PETS	Bypass	1	1667	100	0.21
LT - 35°C - 50km	PETS	Circulation	1	1667	100	0.21
LT - 35°C - 50km	PETS	Transmission	1	2900	2500	9.06
LT - 35°C - 50km	REPEATER	Transmission	1	2900	2500	9.06
LT - 35°C - 50km	DETS	Circ - Cold side	2	2900	250	0.91
LT - 35°C - 50km	DETS	Circ - Hot side	1	2900	1600	5.80
LT - 35°C - 50km	DETS	Peak plant	1	2900	250	0.91
LT - 35°C - 50km	DETS	District pumps				0.00
						29.70
LT - 35°C - 50km						0.00
HT - 120°C - 50km	Power plant	Primary	1	833	700	0.73
HT - 120°C - 50km	PETS	Circulation - borefield	1	1100	700	0.96
HT - 120°C - 50km	PETS	Bypass	1	1100	100	0.14
HT - 120°C - 50km	PETS	Circulation	1	1100	100	0.14
HT - 120°C - 50km	PETS	Transmission	1	1300	2500	4.06
HT - 120°C - 50km	REPEATER	Transmission	1	1300	2500	4.06
HT - 120°C - 50km	DETS	Circ - Cold side	2	1300	250	0.41
HT - 120°C - 50km	DETS	Circ - Hot side	1	2000	1600	4.00
HT - 120°C - 50km	DETS	Peak plant	1	2900	250	0.91
HT - 120°C - 50km	DETS	District pumps				0.00
						15.40
*Assumed 80% pump efficiency						

The figures indicate that the pumps required to feed a 50km network for the VLTHW system are around double that of the pumps required for the MTHW system. This proves to be a considerable energy load aswell as leading to more expensive pump costs.

7.3.1 Carbon Intensity of Heat Supply

Figure 84 shows the carbon intensity of the heat supply without pumping energy. In effect this shows the fundamental carbon intensity of the heat source, regardless of distance from heat load.

The carbon intensity of the supply (when compared with boilers using natural gas or air source heat pumps using grid electricity) is highly dependent on the carbon intensity of the heat pump driving electricity or the lost electrical output (for the VLTHW and MTHW options respectively). The first three groups of results show this.

In order to attribute a carbon factor to the heat taken from power stations the following carbon intensities have been attributed to the electricity lost when heat is extracted at MTHW:

- Coal power plant assuming lost power is replaced by grid marginal plant – 0.519 tCO2/MWh
- Combined Cycle Gas Turbine (CCGT) – 0.4 tCO2/MWh (assuming a 47% efficient plant)
- Carbon Capture and Storage (CCS) – 0.2 tCO2/MWh

If heat was to be made available from a 'zero carbon' source the resultant waste heat can be captured with zero carbon intensity under the MTHW option. It has been assumed that in the VLTHW option the heat pumps continue to make use of grid electricity. The resulting carbon intensities for heat are shown in the fourth group of results.

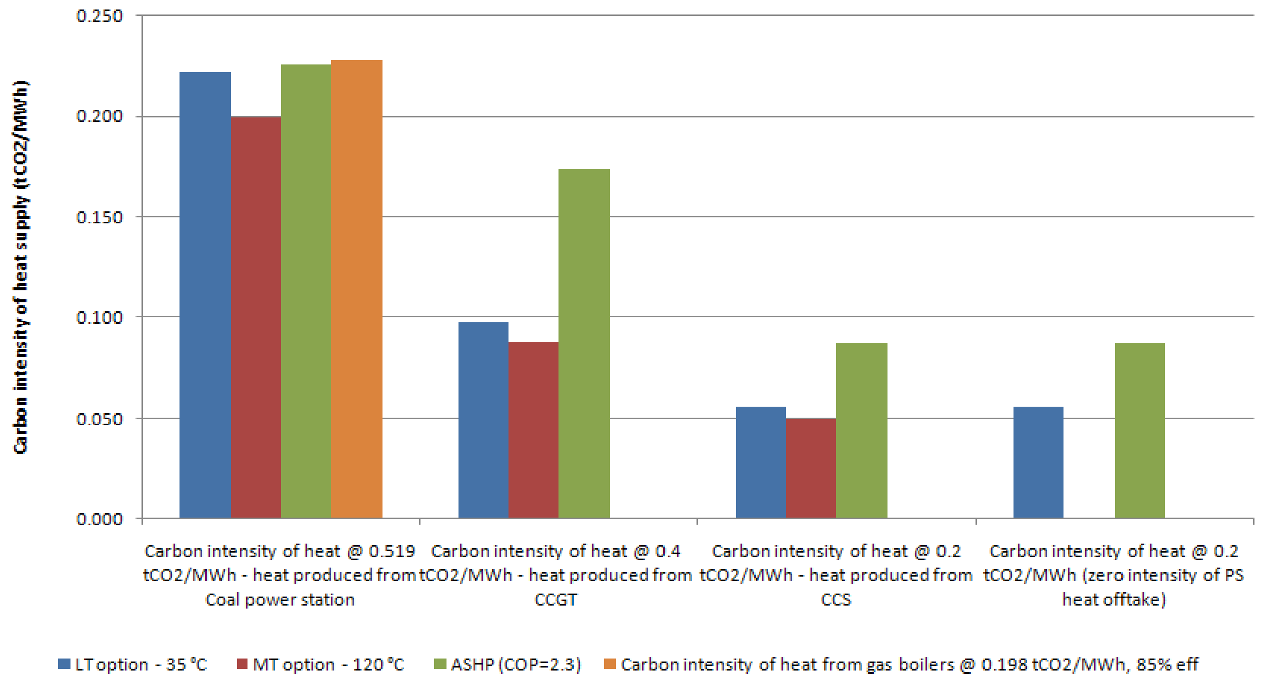

Figure 84 Carbon intensity of heat supply without pumping energy, versus grid electrical carbon intensity

Figure 85 shows the carbon intensity of the heat supply including pumping energy. This shows the carbon intensity of delivered heat at 50km from the load.

The carbon intensity of the system increases significantly when pumping energy is included but is still lower than using air source heat pumps. Assuming heat is available from a zero carbon source the resulting carbon intensity of the MT option is entirely due to pumping energy, but is still only a small fraction of that from air source heat pumps.

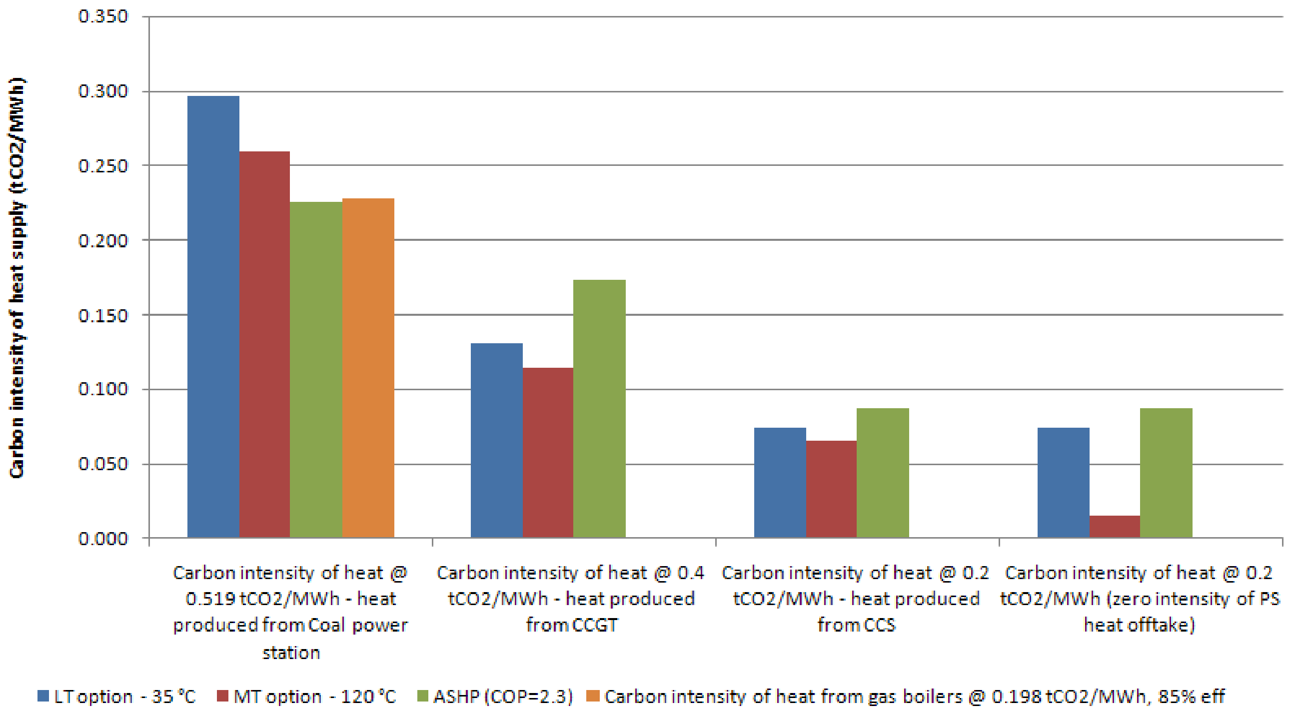

Figure 85 Carbon intensity of heat supply including pumping energy, 50km from load

7.4 Cost of heat

Modelling of the capital, replacement and operational costs has been developed to show an example unit cost of heat for this case study. A methodology has been developed to calculate an equivalent cost of heat based on the net present value of future costs, and discount analysis of future revenues.

7.4.1 Modelling assumptions

The following assumptions have been made in undertaking the analysis:

- Discount rates of 3.5% and 8%
- Replacement periods and percentage of initial costs were selected for each plant item in the bill of quantities
- Maintenance costs of 0.5% of capital investment have been assumed
- Pumping costs, water treatment costs and sacrificial electricity / heat input have been included
- An electrical value of £100/MWh has been used for all electrical consumption / sacrificial output, based on assuming a value in line with future forecasts of wholesale power prices by DECC.
- Staffing levels of 30 persons have been assumed for the system, including a shift team of 4 working a 5 shift pattern, an engineering team of technicians/mangers, plus a small admin team (see Figure 86)
- Table 32below shows the operational costs assumed within the model.

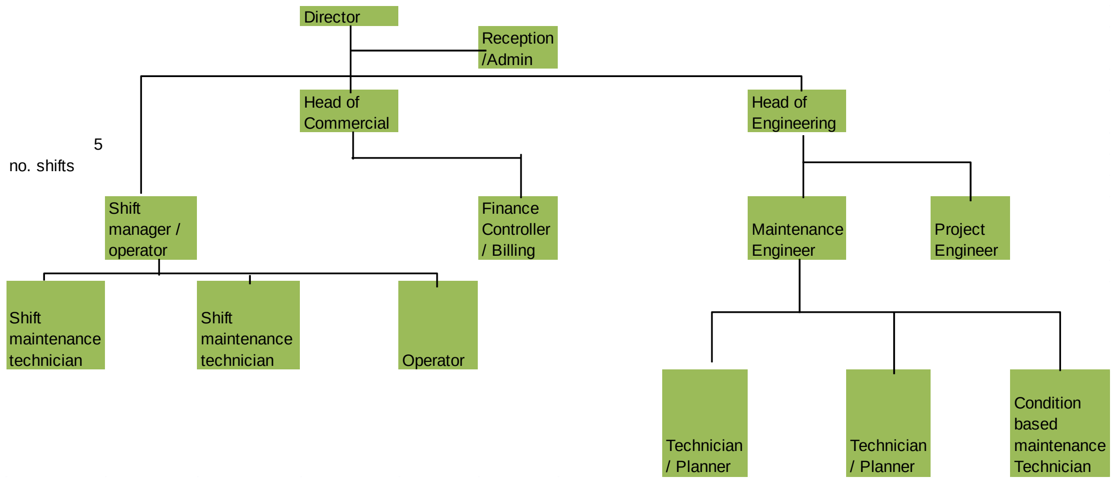

Figure 86 Assumed staffing levels for the heat off take and storage system

Table 32 Operational costs assumed for modelling

	Units	VLTHW option	MTHW option
Staff costs	£/annum	1,950,000	1,950,000
Pumping costs	£/annum	11,030,039	5,829,319
Maintenance costs (@0.5% of CAPEX)	£/annum	2,736,689	1,528,317
Heat pump electrical input	£/annum	33,262,540	-
Lost electrical generation	£/annum	-	19,049,146
Water treatment	£/annum	342,172	362,016

The figures in Table 34 and Table 35 provide a summary breakdown of the testing methodology for both ATES and BTES systems.

Table 34 indicate that, as discussed previously, the pumping costs associated with the VLTHW system are much higher than that of the MTHW system. Furthermore the maintenance cost is almost double that of the MTHW option. This is due to the increased CAPEX value of the VLTHW system associated with the cost of heat pumps and the additional pumping.

The results also indicate that the heat pump electrical input for the VLTHW system is much higher than that of the lost electrical generation for the MTHW system.

7.4.2 Modelling Results – Cost of Heat

Figure 87 below shows the indicative cost of heat from the VLTHW and MTHW options at 50km distances from the city load. These results are generated to understand the order of magnitude of costing for different systems and according to the distance from supply to demand. Additional cost items such as heat take off plant and local heat distribution, land purchase etc are likely to increase the effective heat cost significantly but first indications suggest there is potential for this approach. The high capital and operational costs of the low temperature systems seems to suggest this approach could be marginal versus current conventional heating systems.

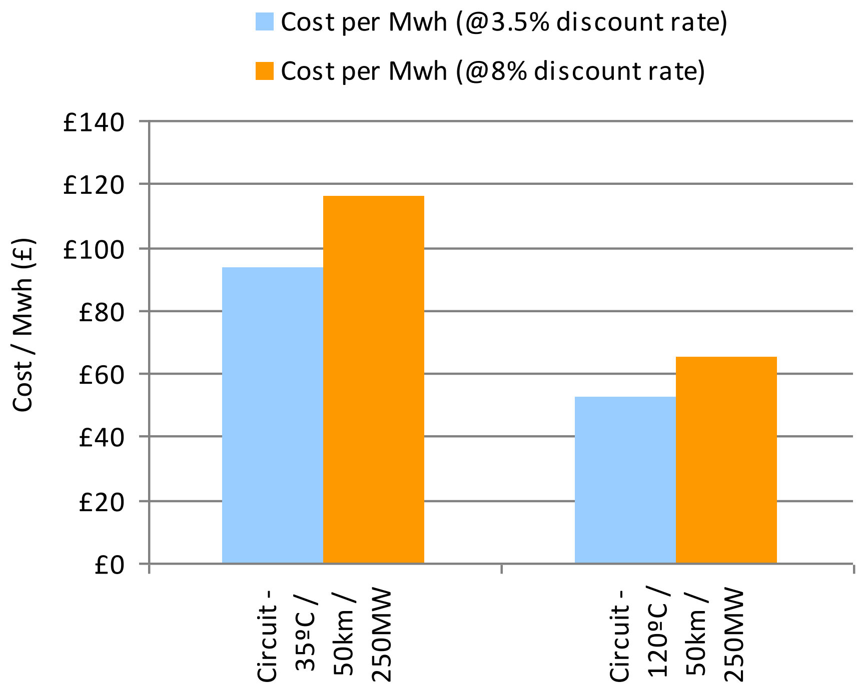

Figure 87 Cost of heat for LT and HT options at 50km distance from city heat load

7.5 Chapter Summary

The following key conclusions and further work have been highlighted.

- The high cost of the heat transmission network dominates all options.
- The carbon intensity of the heat supply is lower from the MTHW option compared with the VLTHW option, the difference is primarily due to the difference in heat pump COP versus the effective COP of the heat off take from a steam turbine (3.6 versus 5)
- The VLTHW option is considerably more expensive than the MTHW option due to the larger diameter pipework and requirement for heat pumps, both of which increase capital cost substantially
- Key parameters include:
    - Cost of large diameter heat network pipes
    - Availability of large diameter pipework and heat pumps
    - Temperature differential which can be generated in the VLTHW network
    - Efficiency- of the ground store
    - Level of maintenance costs (currently based on 0.5% of capital investment) when much of the system cost consists of below ground pipework

8 Identification of Potential Pilot Sites

This section provides a review of the process required for the development of a series of pilot studies.

To summarise the following basic criteria are deemed important for a pilot site

LT BTES

1. Current “waste heat” availability at 120C*
2. Potential to extend into existing or new district heating network*
3. Spatial Opportunity
4. Willing 3rd party

LT ATES

1. Suitable near surface hydrogeology
2. Current “waste heat” availability at 35-50C*
3. Potential to extend into existing or new district heating network*
4. Spatial Opportunity
5. Willing 3rd party
6. No significant regulatory constraints (CAMS/ EA review)

MT ATES

1. Suitable Deep Hydrogeology
2. Current “waste heat” availability at 120C*
3. Potential to extend into existing or new district heating network*
4. Spatial Opportunity
5. Willing 3rd party
6. No significant regulatory constraints (CAMS/ EA review)

*Ideally suited to existing or near-term CHP and district heating schemes

8.1 Delivery Programme for Pilot Project

Table 33 provides an outline breakdown of the different stages whilst the following subsections outline the testing process required for both ATES and BTES systems.

Table 33 Key Phases for Delivery of Pilot Project

Stage	Description
Stakeholder Consultation (early engagement, continued throughout the pilot study as required)	Power Company District Network Operator Local Authority (including EIA screening and scoping) Funder Landowner Environment Agency Government Departments (DEFRA, DECC)
Desktop Study	Geological/ Hydrogeological Spatial Review Supply - Power Station Retrofit Technical Review Demand – Heat Distribution EA Liaison (principally for WR32 Consent to Investigate a Groundwater Source) Environmental Impact Assessment (EIA)
Testing (Note: Phase 3 not completed for post pilot study installations)	Testing Phase 1 – Initial Geological assessment Testing Phase 2 – Single well or borehole installation Testing Phase 3 – Small scale system development and testing

Table 34 and Table 35 provide a summary breakdown of the testing methodology for both ATES and BTES systems.

Table 34 LT and MT ATES Testing Methodology Outline

Phase 1	
Outline	
Small Diameter Borehole drilled to proposed depth of base of aquifer unit for potential use.	Phase aim is to confirm geological sequence, chemical composition of sediment and groundwater, and allow laboratory testing of certain parameters.
Description	
Coring at 5m intervals aside 1m intervals at depth with greatest potential CCTV Chemical Testing	Core would be used for laboratory testing for permeability, porosity and mineral content, as well as geotechnical behaviour at elevated temperatures.
Phase 2	
Outline	
Deep well in Sandstone connected to mobile Boiler unit Single Doublet Well System – Injection/ Abstraction over 3month period Pilot scale water treatment plant	Phase aims to confirm well construction, water treatment required, specific yield and injection to inform numerical modelling and well layout optimisation.
Description	
Yield Testing Abstraction – stepped and constant rate test Injection Testing - stepped and constant rate test Chemical Testing Water treatment testing	Laboratory and field testing used to confirm preferred water treatment process.
Phase 3	
Outline	
Well Field Development. Continue with mobile boiler unit. Construction of 5 abstraction and injection wells, i.e. partial module well field system Install observation wells at certain locations within and beyond well field. Connection to local district heating network if possible Test over 12 month period	Aim of this phase is to test the well field efficiency and validate modelling using a series of observation boreholes. Rejection of heat on abstraction would preferably be to local district heating network, either existing or new.

Figure 88 Well Drilling

Table 35 BTES Testing Methodology Outline

Phase 1	
Outline	
Small Diameter Borehole drilled to proposed depth of thermal store	Phase aim is to confirm geological sequence, drilling methodology and allow laboratory testing of certain parameters.
Description	
Coring at 5m intervals aside 1m intervals at depth with greatest potential	Core would be used for laboratory testing for initial assessment of thermal properties, as well as geotechnical behaviour at elevated temperatures.
Phase 2	
Outline	
Thermal Response Test (TRT) using mobile unit Single borehole installed Groundwater direction and velocity assessed	Phase aim is to confirm thermal properties and thermal movement in the ground due to natural groundwater flow.
Description	
200m deep 150mm Dia, 40mm HDPE pipework Grout thermal conductivity >80% of anticipated thermal conductivity from desktop study Glycol/ water mixture capable of protection to -10°C Heat rate – 60W per linear m of test bore Tri-bore well arrangement to monitor groundwater direction.	Interpretation to include: ○ Undisturbed ground temperature ○ Bulk average thermal conductivity ○ Most cost effective drilling depth The results of the TRT will be used to simulate heat abstraction and rejection to the ground
Phase 3	
Outline	
Borehole Field Development. Move to using mobile boiler unit running at low temperature, i.e. 35-50°C Construction of 20 abstraction and injection wells, i.e. partial module borehole field system Install observation wells at certain locations within and beyond borehole field to assess thermal transport in ground and validate model Connection to small number of local houses if possible. Test over 12 month period	Aim of this phase is to test the borehole array storage efficiency

Figure 89 BTES Thermal Response Set Up

8.2 Pilot Study Analysis

Two case studies are reviewed in more detail in this section, as outlined in Table 5.

Table 36 Pilot Study Case Studies

Power Station	**1 Fiddlers Ferry**		**2 Hartlepool Nuclear Power Station**	
Fuel	Coal		Nuclear	
Location	Merseyside		North East	
Owner	Scottish & Southern Energy plc		British Energy	
MWe	1980		1190	
Storage Option	MT-ATES		MT-ATES	
	16,477,560	16,477,560	9,903,180	9,903,180
Options	**1a**	**1b**	**2a**	**2b**
Heat Demand Area	Liverpool, Warrington, Widnes, Runcorn, St Helens	As 1a Greater Manchester, Bolton, Oldham, Bury.	Hartlepool, Middlesbrough	As 2a Sunderland, Newcastle
Total Heat Demand *(Agglomerations)*	12,885,397	36,273,713	3,316,676	14,952,433
*Distance of Primary Heat Network**	34.5km	128.5km	18.8km	72.7km

* Main road infrastructure used as a proxi for heat distribution. Does not include local distribution.

The two case studies above have been chosen due to their meeting many of the key criteria introduce at the beginning of this chapter.

Both power stations are located in proximity to large areas of heat demand, which is represented as two options for each power station, which represent a small network and a larger network taking into account more of the local heat demand.

It is also assumed that both power stations are able to be adapted in order to produce the desired heat take off temperatures required.

8.2.1 Pilot Study Geological Descriptions

Case Study 1 Fiddler's Ferry

Site location and description

The study area considered falls in the region of Cheshire in North West England. Major nearby cities are Manchester, Liverpool and Southport some 15-20km to the east, southwest and northwest respectively.

Site geology

The Fiddlers Ferry power station and its surrounding is situated in the north of the Cheshire Basin that is part of a complex north-south Permo-Triassic rift system, bounded by faults. The illustration of the geology underneath Fiddlers Ferry Power Station is shown in Figure 90 and has been created on the basis of true scale cross sections forming part of the BGS memoir of the Cheshire Basin and the maps forming part of the Atlas of onshore sedimentary basins in England and Wales. The immediate solid geology of the area is represented by outcropping formations of the Sherwood Sandstone Group. To the east and beyond the Brook House Fault, the Sherwood Sandstone is overlain geological formations of the Mercia Mudstone and Penarth Group.

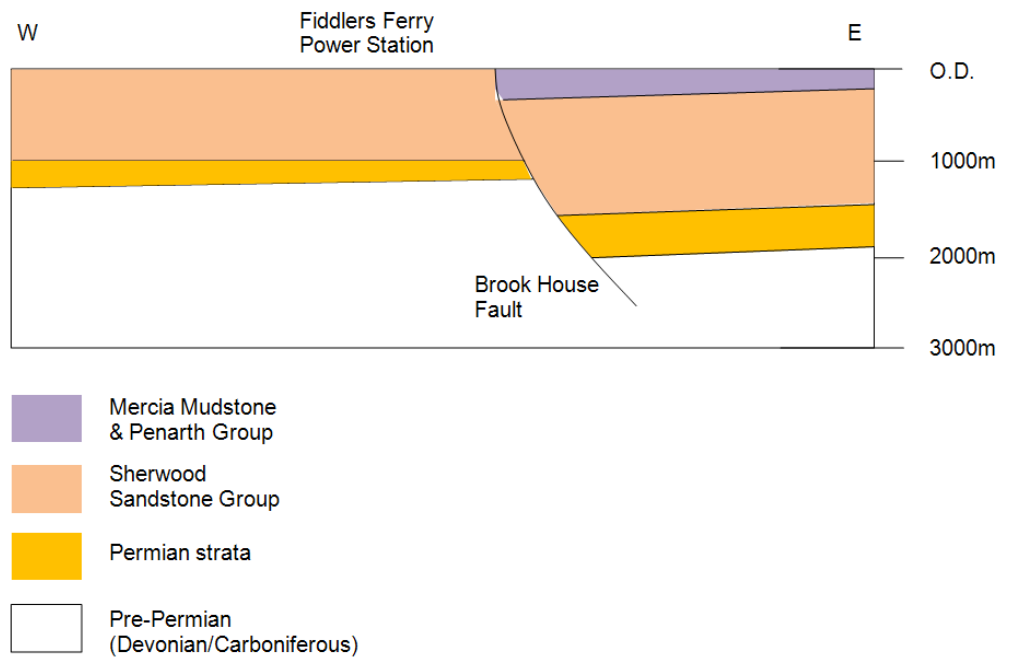

Figure 90 Geological Cross Section beneath Fiddler's Ferry Power Station

Hydrogeology

Geological maps show the site to be located in an area of outcropping Sherwood Sandstones. Records of a borehole drilled south of the site show the Sherwood Sandstone to be overlain by superficial deposits (drift) to a depth of approximately 50m below ground level. The Atlas of Geothermal resources in Europe reports the Sherwood Sandstone at outcrop to have a permeability of 80 – 8000mD. Based on reported test results (see a log of a borehole drilled in the vicinity with data for abstraction rates and rates of drawdown in the Appendix) the permeability of the Sherwood Sandstone underneath the site is estimated in the order of 500mD (0.5m/d). The borehole was abandoned due to high salinity.

Hydrochemistry

A long history of over pumping from boreholes on both sides of the Mersey estuary, particularly at Liverpool and alongside the Manchester Ship Channel, has resulted in saline intrusion into the Permo-Triassic aquifer. Chloride concentrations of 6000mg/l in these areas, combined with high sulphate, have led to the abandonment of many deep boreholes. The remark on the log of the borehole drilled in the vicinity of the site confirms high level of salinity, compromising its use as drinking water.

Case Study 2 Hartlepool Nuclear Power Station

Site location and description

Hartlepool power station is situated on the northern bank of the mouth of the River Tees, 2.5 miles south of Hartlepool in County Durham, North East England.

Site geology

Geological maps show the site to be located in an area of outcropping Sherwood Sandstones at the north-western edge of the East Yorkshire and Lincolnshire Permo-Triassic Basin. At this location however, borehole logs suggest the sandstone to be overlain by at least 30m of superficial deposits (Till) over 13m of Keuper Marl forming part of the Mercia Mudstone Group.

In this basin the Triassic Sherwood Sandstone is separated from the Basal Permian Sands by an evaporite sequence and the two sandstones form distinct reservoirs" attaining a maximum thickness of over 500m. A simplified cross section is shown in Figure 91.

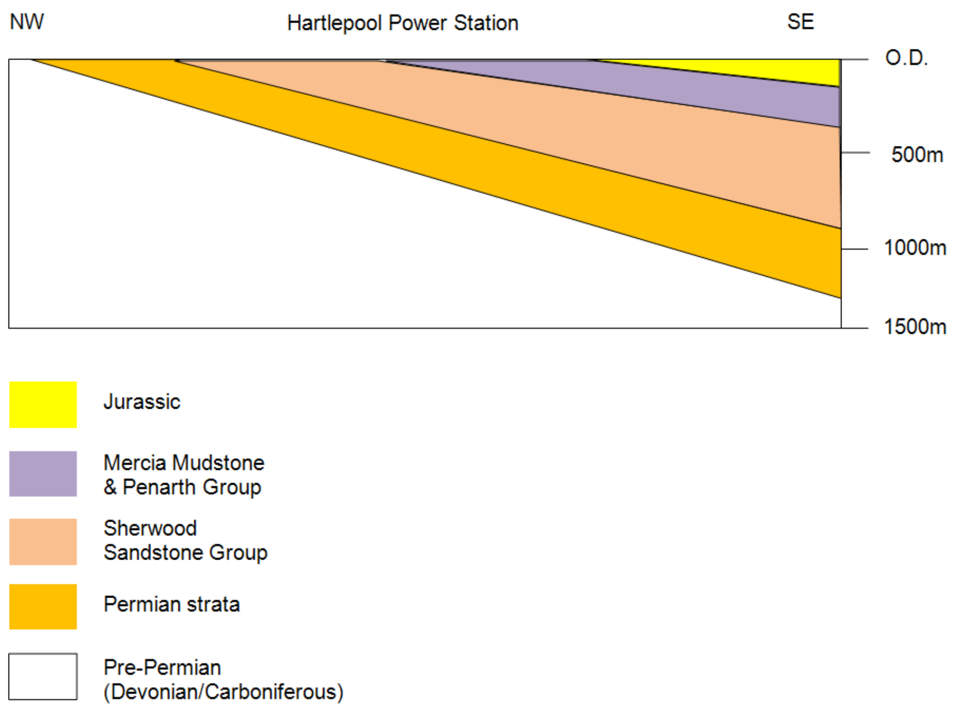

Figure 91 Geological Cross Section beneath Hartlepool Power Station

Hydrogeology

The porosity generally exceeds 20% and the average permeability is considered to be about 250mD (0.2m/d). Such an estimate for the average permeability is probably a good first estimate where the Sherwood Sandstone is overlain by Mercia Mudstone. This concurs with permeability values (0.15m/d, 0.4m/d) found at Little Scar some 3km north of the site.

Hydrochemistry

The East Yorkshire and Lincolnshire basins contain water with salinity lower than or equal to sea water. Figure 92 indicates low levels of salinity expressed as total dissolved solids (TDS). However, the close proximity to the sea may have an effect on salinity levels especially during operations of water pumping and injection.

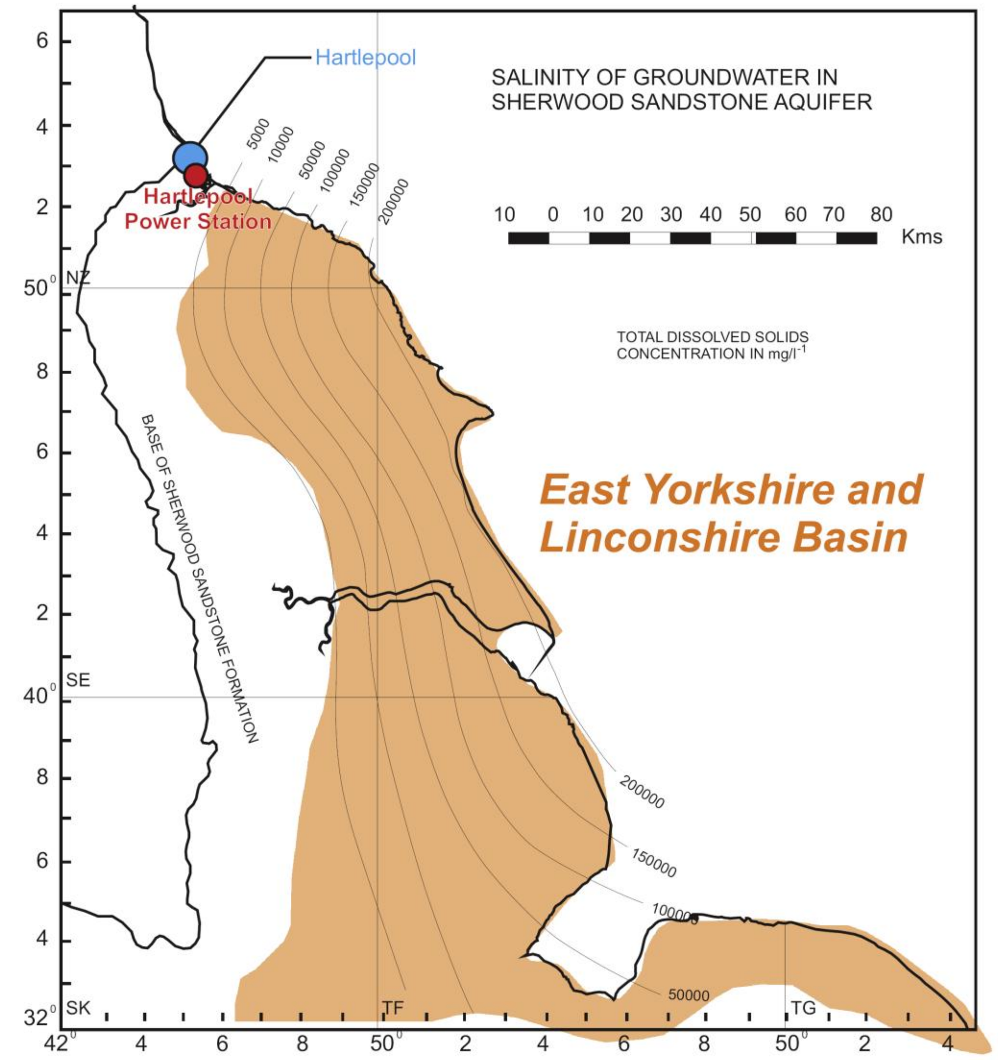

Figure 92 Salinity measured in Total Dissolved Solids (TDS) in the East and Linconshire Basin

8.2.2 Pilot Study GIS Analysis Descriptions

Figure 61 and Figure 42 show the interpretive GIS mapping for both sites indicating the following

1. Location of the Power Station
2. Presence of underlying Deep Sandstone aquifer
3. High Heat Dense areas
4. Benefits of Agglomeration Exercise

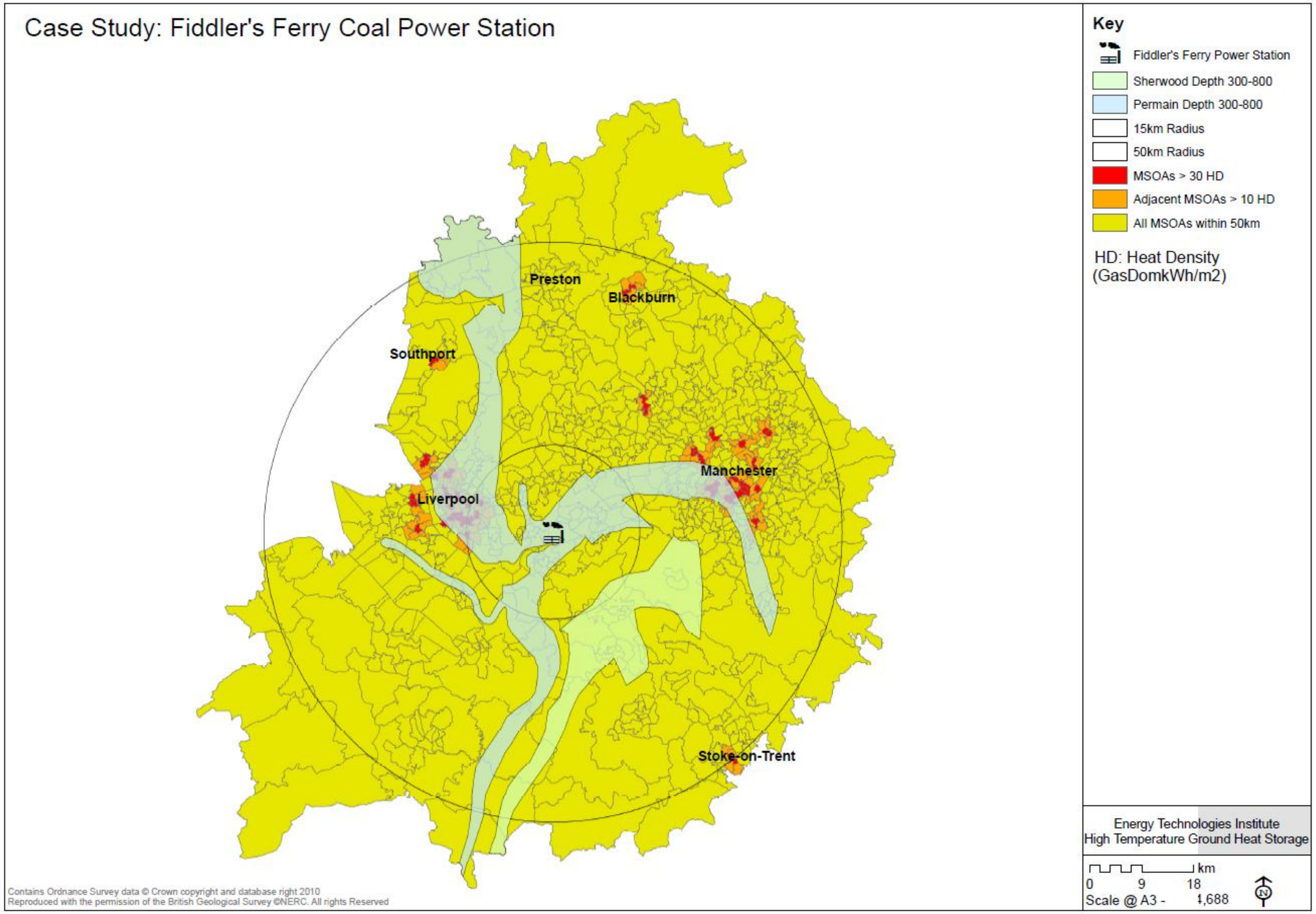

Figure 93 Fiddler's Ferry (50km) versus Deep Sandstone and Heat Density

Benefits of agglomeration exercise

X = All MSOAs combined heat density within 50km = 0.72 kWh/m2

Y = All agglomerated areas combined heat density within 50 km = 16.4 kWh/m2

Ratio = 4.4%

Note X had a total area of 9194.6 sq km

And Y had a total area of 446.75 km

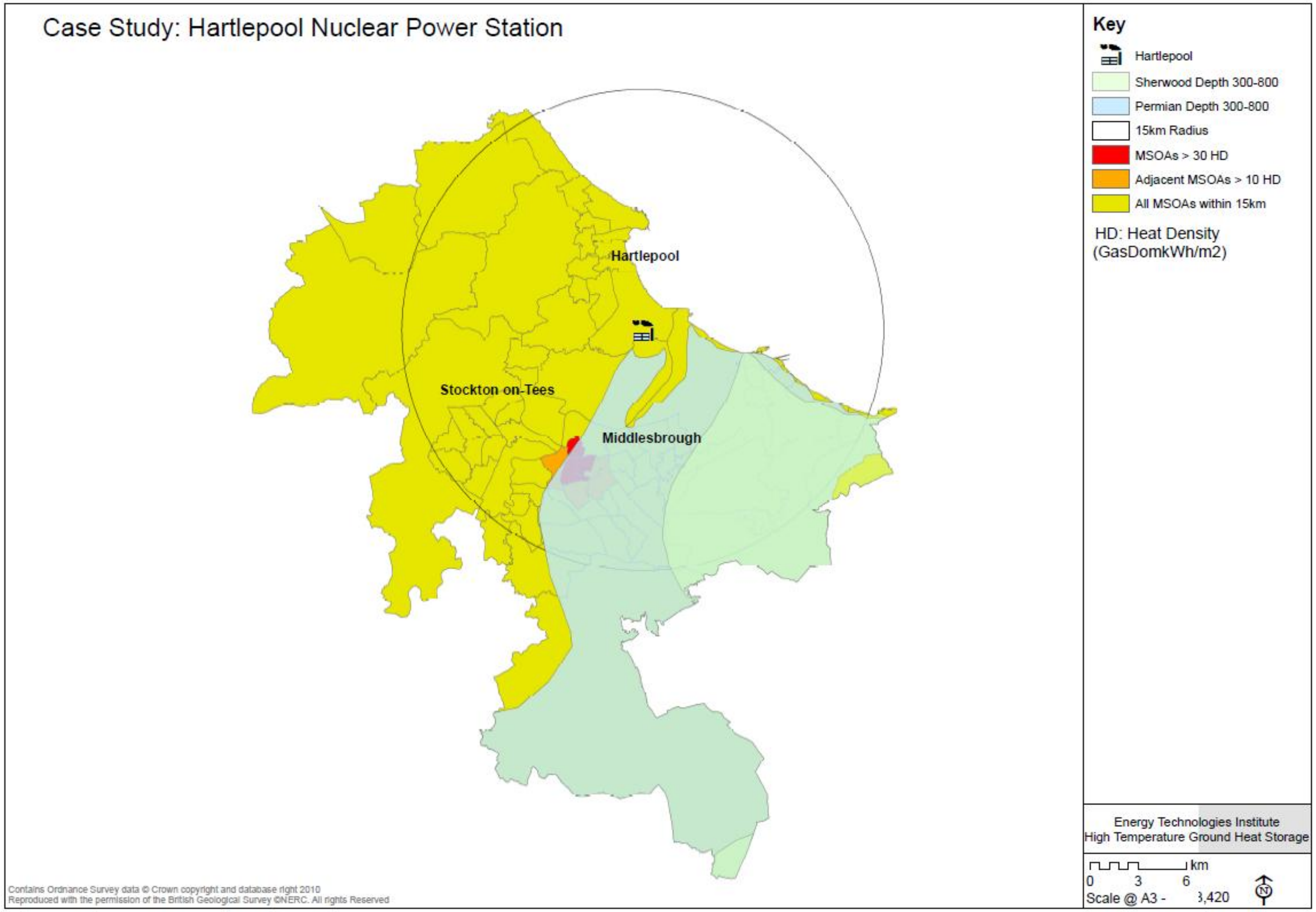

Figure 94 Hartlepool Nuclear Power Station (15km) versus Deep Sandstone and Heat Density

Benefits of agglomeration exercise

X (all MSOAs combined heat density within 15km) = 3.44kWh/m^2

Y = all agglomerated areas (30 + Adjacent 10) combined heat density within 15 km = 21.77 kWh/m^2

Ratio = 15.8%

Note X had a total area of 837.24 sq km

And Y had a total area of 11.67 sq km

8.2.3 Energy Distribution System

For system schematics, please refer to appendix A. Contained within the appendices are the following indicative drawings for the system reviewed in this chapter:

1. M100-01 – Indicative Borehole Field Layout
2. M700-01 - Option 1– VLTHW 35°C - 50km - 250MW
3. M700-02 - Option 2 – MTHW 120°C - 50km - 250MW

8.2.4 Modelling of capacity and operation over typical year

VLTHW System - Assumptions and Heat Balances

The following heat balances are based on heat demand data taken from the Department of Energy and Climate Change. The loads take into account:

- Heat demand through domestic water demand consumption
- Heat network losses through the distribution network to the heat centres
- Losses through the ground storage. Thermal efficiency assumed at 85% for LT system
- The heat demand for the low temperature circuits takes into account the uplift in heat output to the district heating network via the heat pumps (CoP of 3.6)

Option 1: VLTHW Fiddlers Ferry Coal Fired Power Station

Option 1A (Figure 95): Allowing for the storage of heat from the power station direct to the ground would lead to an excess of heating availability in the magnitude of Ca. 5,496,339 MWh

In order to balance the heat discharge / storage, the required heat draw off from the power station would be reduced

Or

The heat network area should be expanded to increase the heat demand.

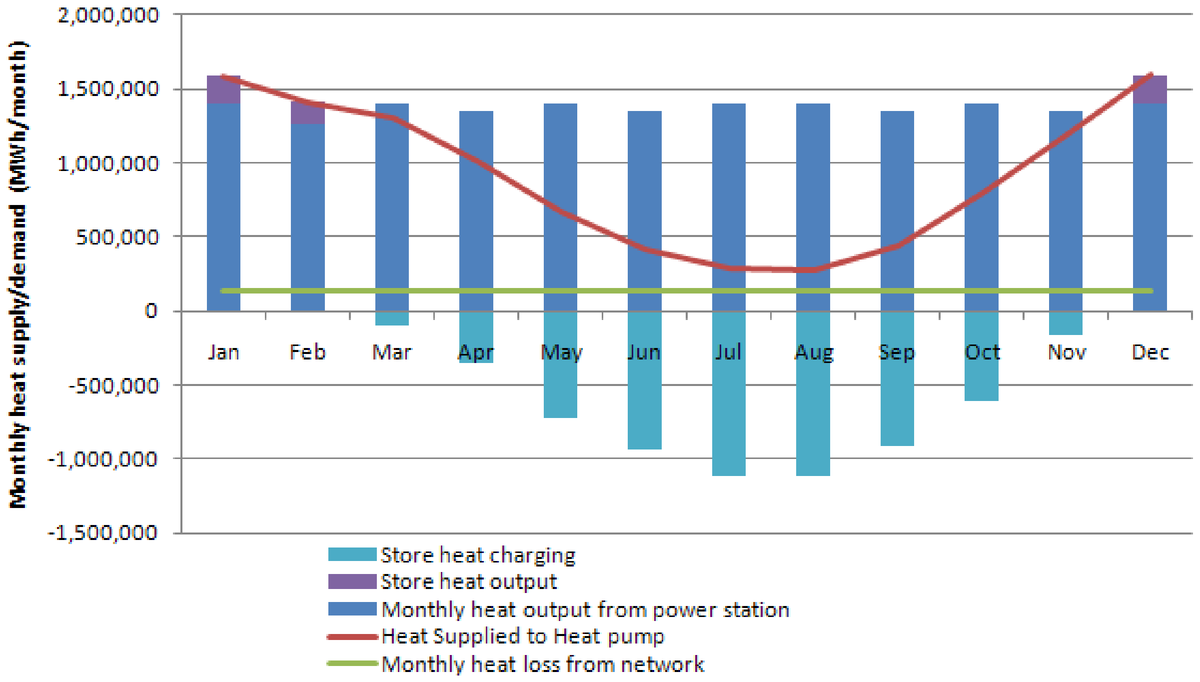

Figure 95 VLTHW: Option 1A - Fiddlers Ferry Coal Power Station - Monthly Heat Balance

Option 1B (Figure 96): Allowing for the storage of heat from the power station direct to the ground would lead to a shortfall of heating availability in the magnitude of Ca. 14,435,704 MWh.

This would mean that either the area served by the heat network should be reduced, therefore reducing the demand ;

Or

An alternate, low carbon producing (biomass, CHP, etc), be provided to make up the shortfall.

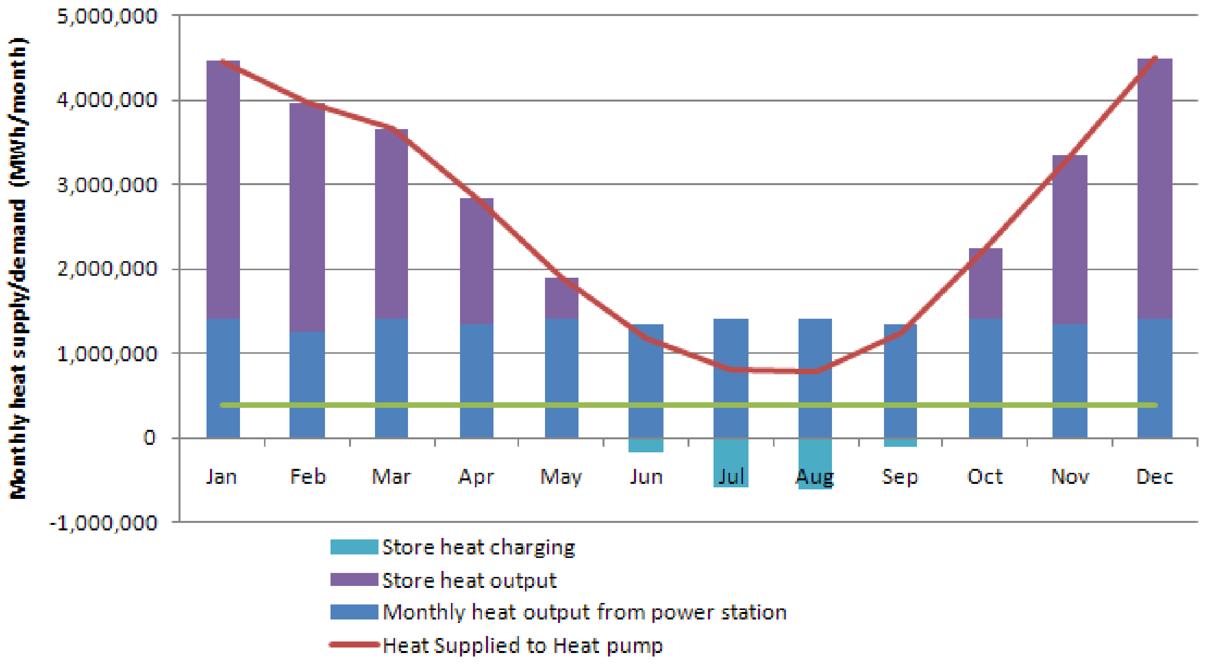

Figure 96 VLTHW: Option 1B - Fiddlers Ferry Coal Power Station - Monthly Heat Balance

Option 2: VLTHW Hartlepool nuclear power station

Option 2A (Figure 97): Allowing for the storage of heat from the power station direct to the ground would lead to an excess of heating availability in the magnitude of Ca. 7,076,635 MWh

In order to balance the heat discharge / storage, the required heat draw off from the power station would be reduced

Or

The heat network area should be expanded to increase the heat demand

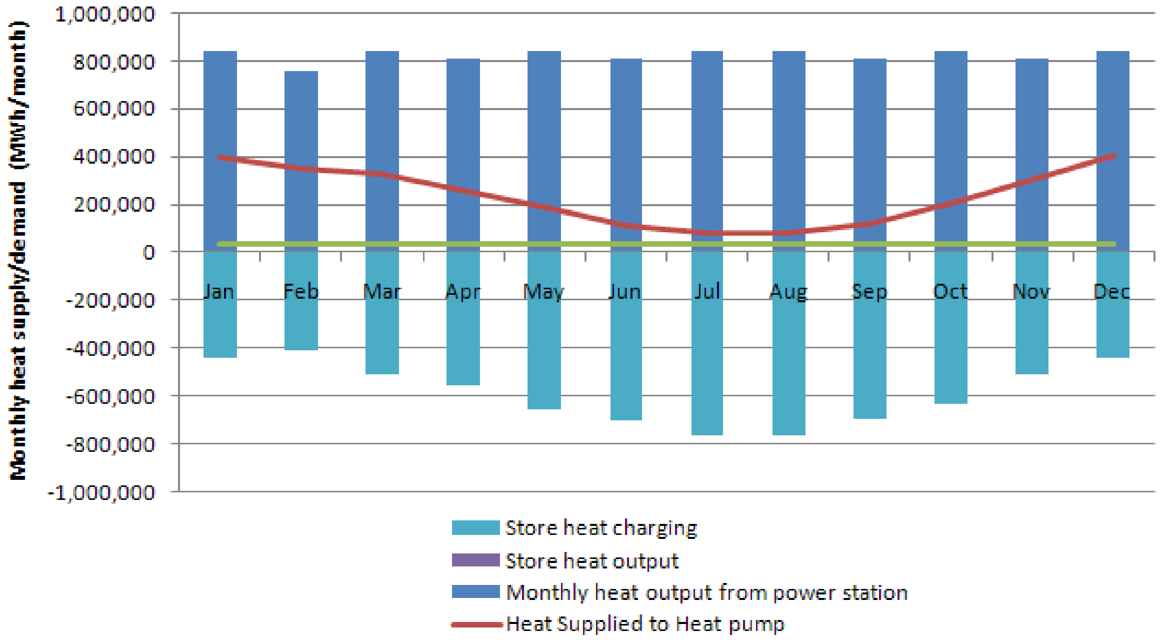

Figure 97 VLTHW: Option 2A - Hartlepool Power Station - Monthly Heat Balance

Option 2B (Figure 98): Allowing for the storage of heat from the power station direct to the ground would lead to a shortfall of heating availability in the magnitude of Ca. 2,839,616 MWh

This would mean that either the area served by the heat network should be reduced, therefore reducing the demand.

Or

An alternate, low carbon producing (biomass, CHP, etc), be provided to make up the shortfall

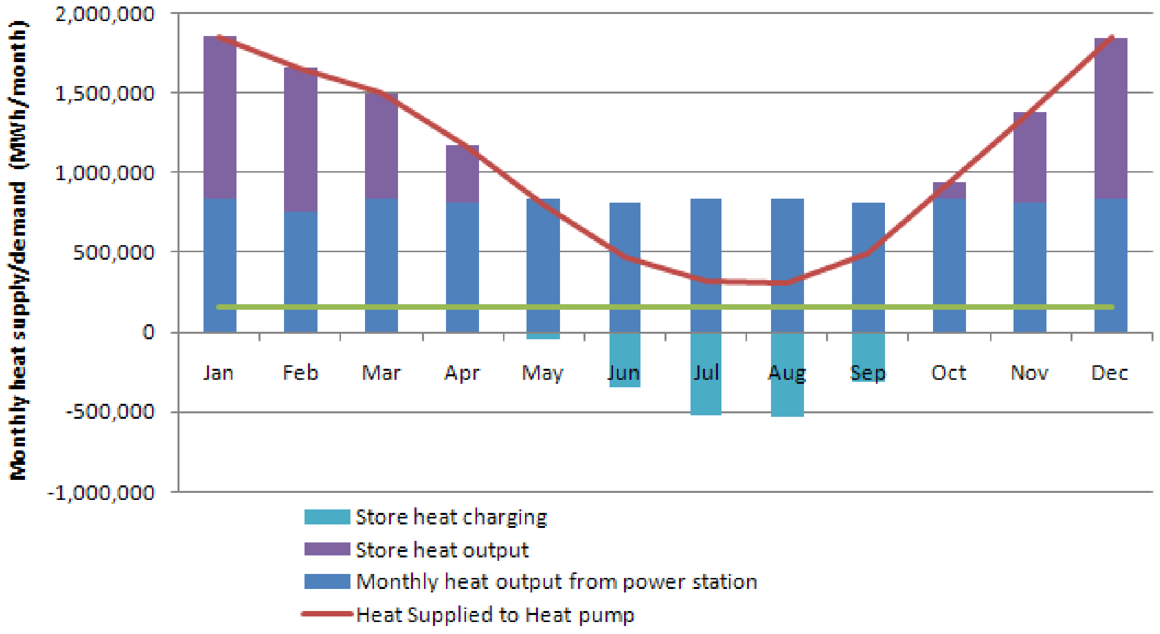

Figure 98 VLTHW: Option 2B - Hartlepool Power Station - Monthly Heat Balance

MTHW System - Assumptions and Heat Balances

The following heat balances are based on real world data of heat demand from the areas as detailed in Table 36.. The loads take into account:

1. Heat demand through domestic water demand consumption
2. Heat network losses through the distribution network to the heat centres
3. Losses through the ground storage

The heat demand for the medium temperature circuits takes into account increase in heat output afforded to the heat network from the application of the Z factor to the turbine cycle

Option 1: VLTHW Fiddlers Ferry Coal Fired Power Station

Option 1A (Figure 99): Allowing for the storage of heat from the power station direct to the ground would lead to an excess of heating availability in the magnitude of Ca. 949,749 MWh

In order to balance the heat discharge / storage, the required heat draw off from the power station would be slightly reduced. A heat takeoff of 1800 MWth is assumed from the power station, corresponding in a loss of 360 MWe peak electrical production, equivalent of around 3,100,000 MWh/Annum

This option presents a near ideal balance between storage and discharge. The peak heating load would lead to 2 No. distribution networks from the store, each in the region of 1600mm diameter pipework

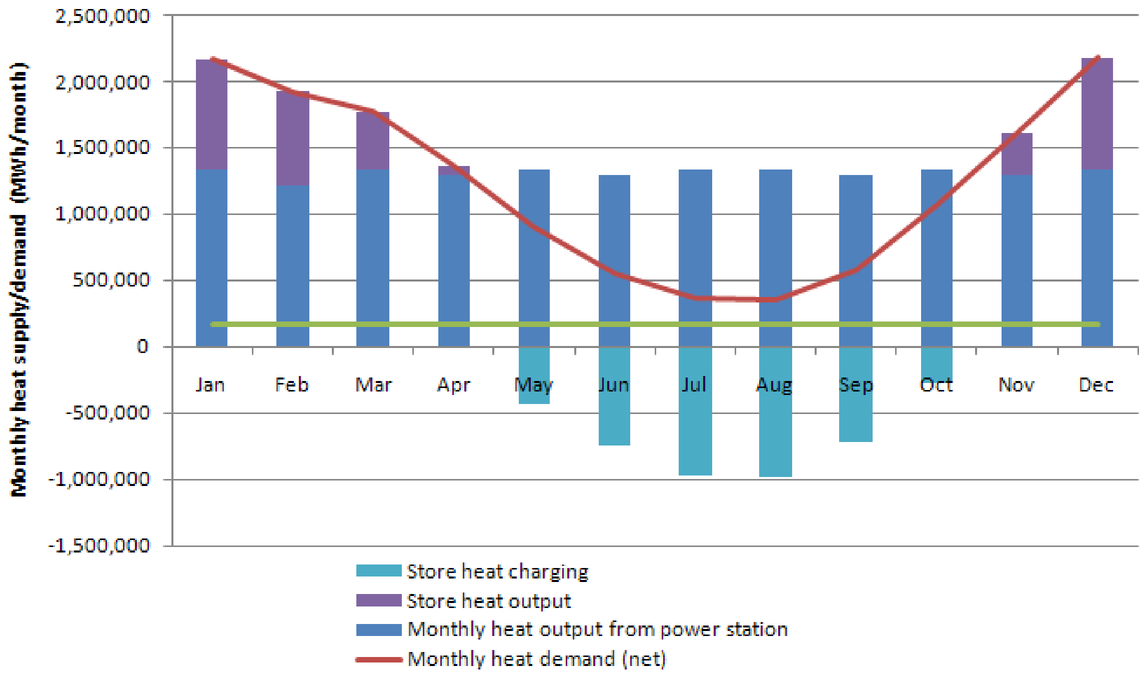

Figure 99 MTHW: Option 1A - Fiddlers Ferry Coal Power Station - Monthly Heat Balance

Option 1B (Figure 100): Allowing for the storage of heat from the power station direct to the ground would lead to a shortfall of heating availability in the magnitude of Ca. 25,946,770 MWh

This would mean that either the area served by the heat network should be reduced, therefore reducing the demand.

Or

An alternate, low carbon producing (biomass, CHP, etc), be provided to make up the shortfall

A heat takeoff of 1800 MWth is assumed from the power station, corresponding in a loss of 360 MWe peak electrical production, equivalent of around 3,100,000 MWh/Annum.

The peak heating load would lead to 2 No. distribution networks from the store, each in the region of 1600mm diameter pipework

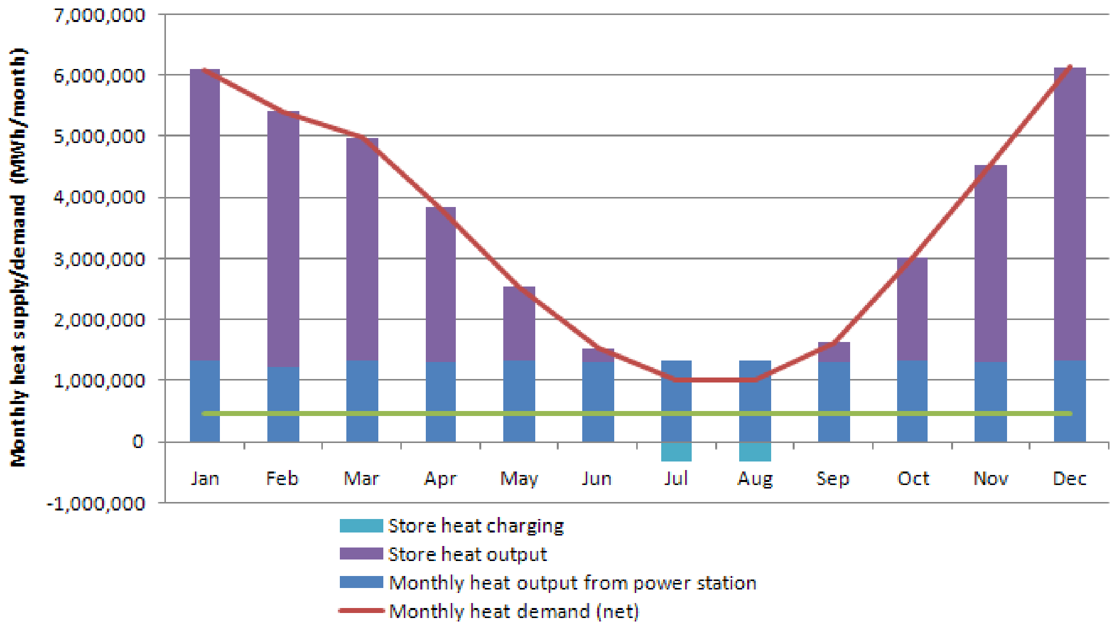

Figure 100 MTHW: Option 1B - Fiddlers Ferry Coal Power Station - Monthly Heat Balance

Option 2: MTHW Hartlepool nuclear power station

Option 2A (Figure 101): Allowing for the storage of heat from the power station direct to the ground would lead to a slight excess of heating availability in the magnitude of Ca. 47,378 MWh

In order to balance the heat discharge / storage, the required heat draw off from the power station would be slightly reduced.

Or

The heat network area should be expanded to increase the heat demand

A heat takeoff of 430 MWth is assumed from the power station, corresponding in a loss of 86 MWe peak electrical production, equivalent of around 753,360 MWh/Annum.

The peak heating load would lead to 2 No. distribution networks from the store, each in the region of 1200mm diameter pipework

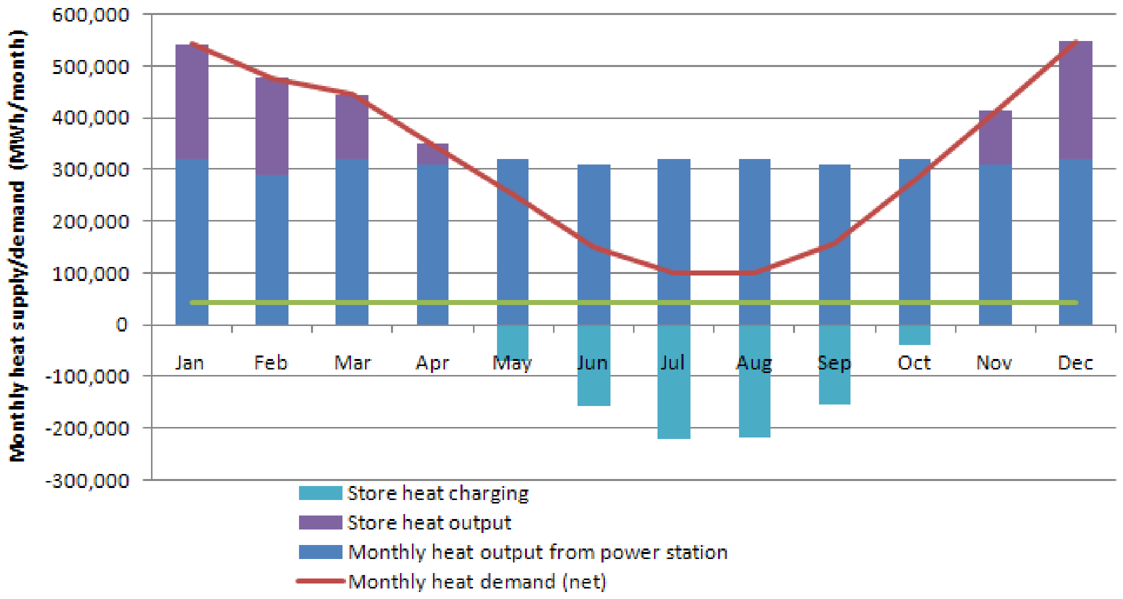

Figure 101 MTHW: Option 2A - Hartlepool Power Station - Monthly Heat Balance

Option 2B (Figure 102): Allowing for the storage of heat from the power station direct to the ground would lead to a shortfall of heating availability in the magnitude of Ca. 8,435,299 MWh

This would mean that either the area served by the heat network should be reduced, therefore reducing the demand.

Or

An alternate, low carbon producing (biomass, CHP, etc), be provided to make up the shortfall

A heat takeoff of 1950 MWth is assumed from the power station, corresponding in a loss of 390 MWe peak electrical production, equivalent of around 3,416,400 MWh/Annum.

The peak heating load would lead to 2 No. distribution networks from the store, each in the region of 1600mm diameter pipework

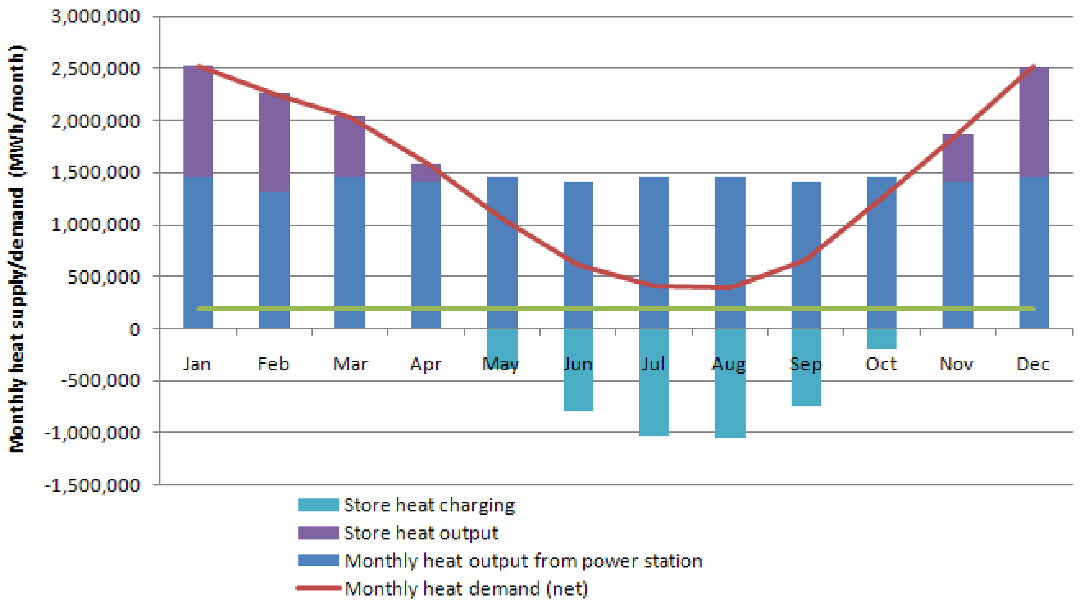

Figure 102 MTHW: Option 2B - Hartlepool Power Station - Monthly Heat Balance

VLTHW and MTHW System Conclusions

VLTHW System Conclusions

The following key conclusions have been highlighted as follows:

- All options for the low temperature system as calculated would represent a either an excess or a shortage of heat, this would suggest that further analysis is required in order to tweak the network area which can be served under each option

MTHW System Conclusions

The following key conclusions have been highlighted as follows:

- Options 1A and 1B of the medium temperature system, which relate to the Fiddlers Ferry coal fired plant would appear to give the best energy balance in terms of heat stored / heat discharged from ground.
- Option 2A of the MTHW system, which relates to the Hartlepool nuclear power station represents a good example of heat output being balanced to meet the storage / discharge requirements. These benefits can be utilised for a relatively small reduction in electrical energy output / annum.

8.2.5 Costing and Financial Model

Cost of Heat

Table 37 and Table 38 below set out the operational modelling results for each option for the VLTHW and MTHW systems respectively. **Modelling Assumptions**

The following assumptions have been made in undertaking the analysis:

1. Discount rates of 3.5% and 8%
2. Replacement periods and percentage of initial costs were selected for each plant item in the bill of quantities, these bills can be found under Appendix B
3. Staffing levels are as outlined in 7.4.1 on page 71.
4. Maintenance costs of 0.5% of capital investment have been assumed
5. Pumping costs, water treatment costs and sacrificial electricity / heat input have been included as indicated in Table 39 and Table 40.
6. An electrical value of £100/MWh has been used for all electrical consumption / sacrificial output, based on assuming a value in line with future forecasts of wholesale power prices by DECC.
7. A Z-factor of 5 has been assumed for all lost electrical output associated with the medium temperature system.

The results indicate that the heat losses from the network increase dramatically from options 1a and 2a to 1b and 2b respectively, this is due to the increase in distribution length, whereas the losses from the ground store reduce. This is due to the fact that less heat shall be stored within the ground as more is required by the heat network.

The MTHW results show that a large heat take off from the power station is required in order to provide the heat demand from the network.

Table 37 Results from operational modelling (VLTHW)

		VLTHW - 1A	VLTHW - 1B	VLTHW - 2A	VLTHW - 2B
Heat supply upto HPs (net)	MWh	9,306,120	26,197,681	2,395,377	10,798,980
Heat loss from ground store	MWh	903,798	224,854	1,061,495	262,854
Heat loss from network	MWh	1,675,102	4,715,583	431,168	1,943,816
Heat supply (gross offtake from turbine)	MWh	16,477,560	16,477,560	9,903,180	9,903,180
Heat offtake from power station	MW	790	1,600	300	900
Total heat from heat pumps	MWh	14,560,498	40,989,295	3,747,844	16,896,250
Annual Demand	MWh	-	-	-	-

Table 38 Results from operational modelling (MTHW)

		MTHW - 1A	MTHW - 1B	MTHW - 2A	MTHW - 2B
Heat supply upto HPs (net)	MWh	-	-	-	-
Heat loss from ground store	MWh	1,033,747	163,800	215,487	1,054,663
Heat loss from network	MWh	1,932,810	5,441,057	497,501	2,242,865
Heat supply (gross offtake from turbine)	MWh	15,768,000	15,768,000	3,766,800	17,082,000
Heat offtake from power station	MW	1,800	1,800	430	1,950
Total heat from heat pumps	MWh	-	-	-	-
Annual Demand	MWh	12,885,397	36,273,713	3,316,676	14,952,434

Table 39 and Table 40 below set out the operational costs for each option for the VLTHW and MTHW systems respectively. Figures for staff costs are taken as constant across all models, as it is assumed that a robust staff has been included for in the calculations, hence no larger team is required to run a larger network. The table also shows that the pumping costs for each system present a large annual outlay. The MTHW table shows that the pumping costs associated with the MTHW are far lower than that of the VLTHW system as previously noted within this report.

The lost electrical output for the MTHW system and the heat pump input energy for the VLTHW system are comparable for the options 1a and 2a. However, for options 1b and 2b, the electrical energy required to drive the heat pumps far exceeds that of the electrical power lost through the alteration of the steam cycle to allow the take off of the higher temperature heat. Table 41 and Table 42 break down the energy associated with pumping for each option for the VLTHW and MTHW systems respectively.

Table 39 Operational costs assumed for modelling (VLTHW)

		VLTHW - 1A	VLTHW - 1B	VLTHW - 2A	VLTHW - 2B
Staff costs	£ / annum	£1,950,000	£1,950,000	£1,950,000	£1,950,000
Pumping energy		53%	53%	53%	53%
Pumping Cost	£	59,149,110	141,814,326	12,786,271	70,686,630
Lost electrical output	MWh electric	-	-	-	-
Heat pump electrical input	MWh electric	4,044,583	11,385,915	1,041,068	4,693,403

Table 40 Operational costs assumed for modelling (MTHW)

		MTHW - 1A	MTHW - 1B	MTHW - 2A	MTHW - 2B
Staff costs	£ / annum	£1,950,000	£1,950,000	£1,950,000	£1,950,000
Pumping energy		54%	54%	54%	54%
Pumping Cost	£	£603,569	£1,330,129	£112,879	£913,854
Lost electrical output	MWh electric	3,153,600	3,153,600	753,360	3,416,400
Heat pump electrical input	MWh electric	-	-	-	-

Table 41 Energy Consumed through Pumping (Low Temperature)

Circuit	Plant space	Pumpset	Duty pumps	Duty (l/s)	Head (kPa)	Pump energy consumption (MWh)
LT - 1A	Power plant	Primary	1	9449	600	32902
LT - 1A	PETS	Circulation - borefeld	1	9449	1600	87740
LT - 1A	PETS	Bypass	4	2360	400	21914
LT - 1A	REPEATER	Transmission	4	9449	1600	350959
LT - 1A	DETS	Circ - Cold side	1	9449	250	13709
LT - 1A	DETS	Circ - Hot side	1	25000	1600	232140
LT - 1A	DETS	District pumps				0
						739,364
Circuit	**Plant space**	**Pumpset**	**Duty pumps**	**Duty (l/s)**	**Head (kPa)**	**Pump energy consumption (MWh)**
LT - 1B	Power plant	Primary	2	8500	600	59196
LT - 1B	PETS	Circulation - borefeld	1	19000	1600	176426
LT - 1B	PETS	Bypass	4	4750	400	44107
LT - 1B	REPEATER	Transmission	10	8500	2500	1233244
LT - 1B	DETS	Circ - Cold side	1	19000	250	27567
LT - 1B	DETS	Circ - Hot side	1	25000	1600	232140
LT - 1B	DETS	District pumps				0
						1,772,679
Circuit	**Plant space**	**Pumpset**	**Duty pumps**	**Duty (l/s)**	**Head (kPa)**	**Pump energy consumption (MWh)**
LT - 2A	Power plant	Primary	1	3600	600	12536
LT - 2A	PETS	Circulation - borefeld	1	3600	1600	33428
LT - 2A	PETS	Bypass	4	900	400	8357
LT - 2A	REPEATER	Transmission	1	3600	1600	33428
LT - 2A	DETS	Circ - Cold side	1	3600	250	5223
LT - 2A	DETS	Circ - Hot side	1	7200	1600	66856
LT - 2A	DETS	District pumps				0
						159,828
Circuit	**Plant space**	**Pumpset**	**Duty pumps**	**Duty (l/s)**	**Head (kPa)**	**Pump energy consumption (MWh)**
LT - 2B	Power plant	Primary	2	5500	600	38303
LT - 2B	PETS	Circulation - borefeld	1	11000	1600	102142
LT - 2B	PETS	Bypass	4	2750	400	25535
LT - 2B	REPEATER	Transmission	6	5500	2500	478789
LT - 2B	DETS	Circ - Cold side	1	11000	250	15960
LT - 2B	DETS	Circ - Hot side	1	24000	1600	222854
LT - 2B	DETS	District pumps				0
						883,583

Table 42 Energy Consumed through Pumping (Medium temperature)

Circuit	Plant space	Pumpset	Duty pumps	Duty (l/s)	Head (kPa)	Pump energy consumption (MWh)
MT - 1A	Power plant	Primary	1	11000	600	39026
MT - 1A	PETS	Circulation - borefeld	1	11000	1600	104069
MT - 1A	PETS	Bypass	4	2750	400	26017
MT - 1A	REPEATER	Transmission	4	11000	1600	416275
MT - 1A	DETS	Circ - Cold side	1	1300	250	1922
MT - 1A	DETS	Circ - Hot side	1	11000	250	16261
MT - 1A	DETS	District pumps				0
						603,569
Circuit	**Plant space**	**Pumpset**	**Duty pumps**	**Duty (l/s)**	**Head (kPa)**	**Pump energy consumption (MWh)**
MT - 1B	Power plant	Primary	1	11000	600	39026
MT - 1B	PETS	Circulation - borefeld	1	11000	1600	104069
MT - 1B	PETS	Bypass	4	2750	400	26017
MT - 1B	REPEATER	Transmission	10	11000	1600	1040688
MT - 1B	DETS	Circ - Cold side	1	11000	250	16261
MT - 1B	DETS	Circ - Hot side	1	11000	1600	104069
MT - 1B	DETS	District pumps				0
						1,330,129
Circuit	**Plant space**	**Pumpset**	**Duty pumps**	**Duty (l/s)**	**Head (kPa)**	**Pump energy consumption (MWh)**
MT - 2A	Power plant	Primary	1	2600	600	9224
MT - 2A	PETS	Circulation - borefeld	1	2600	1600	24598
MT - 2A	PETS	Bypass	4	2750	400	26017
MT - 2A	REPEATER	Transmission	1	2600	1600	24598
MT - 2A	DETS	Circ - Cold side	1	2600	250	3843
MT - 2A	DETS	Circ - Hot side	1	2600	1600	24598
MT - 2A	DETS	District pumps				0
						112,879
Circuit	**Plant space**	**Pumpset**	**Duty pumps**	**Duty (l/s)**	**Head (kPa)**	**Pump energy consumption (MWh)**
MT - 2B	Power plant	Primary	1	11000	600	39026
MT - 2B	PETS	Circulation - borefeld	1	11000	1600	104069
MT - 2B	PETS	Bypass	4	2750	400	26017
MT - 2B	REPEATER	Transmission	6	11000	1600	624413
MT - 2B	DETS	Circ - Cold side	1	11000	250	16261
MT - 2B	DETS	Circ - Hot side	1	11000	1600	104069
MT - 2B	DETS	District pumps				0
						913,854

Modelling Results – Cost of heat

All variations of the case studies as discussed in this chapter have been modelled in order to ascertain the expected cost of heat per MWh, the results of the modelling are shown in Figure 103 below.

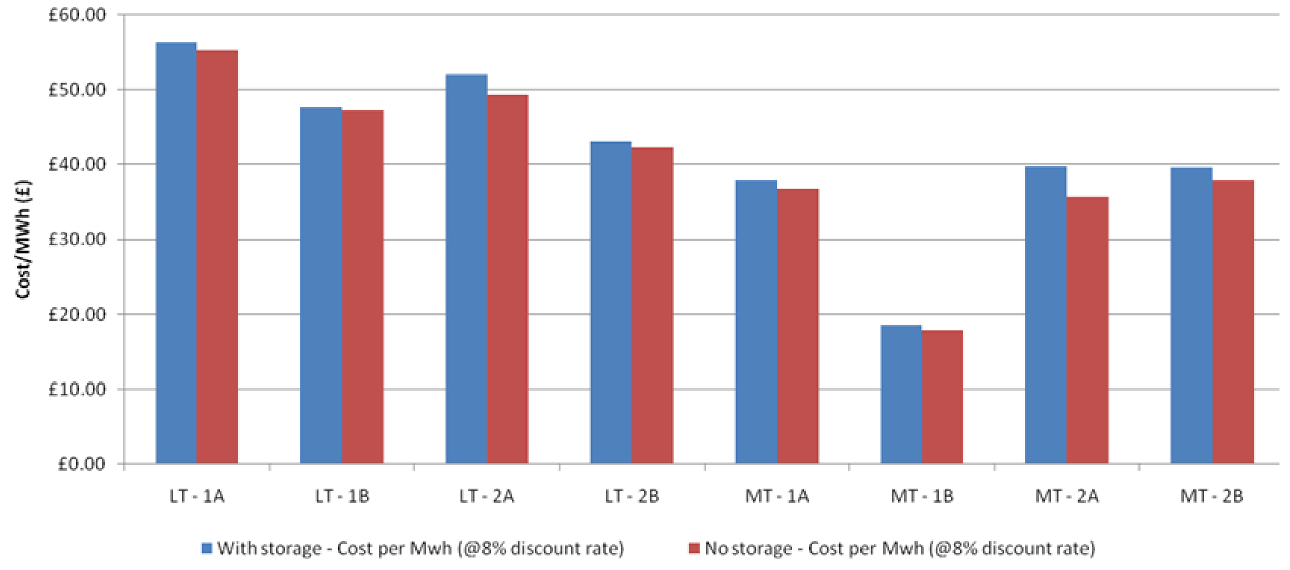

Figure 103 Cost of heat comparison (with 8% discount rate)

The results show that the cost of heat for the VLTHW options 2a and 2b present the cheapest options in terms of cost / MWh (£). This is due to the distances involved within these options being smaller when compared to options 1a and 1b.

Whilst for the MTHW system, the cheapest option would be option 1b, this is due to the economies of scale due to the length of the heat network (ca. 130km).

Table 43 and Table 44 outline the CAPEX as broken down element by element for each of the case study options assessed, for the VLTHW and MTHW systems respectively.

Table 43 Elemental breakdown of CAPEX for VLTHW options

Option	VLTHW - 1A	VLTHW - 1B	VLTHW - 2A	VLTHW - 2B
Distance (kM)	**35**	**130**	**20**	**75**
Pumps (£)	12,600,000	26,600,000	6,800,000	16,700,000
Pipework (£)	497,000,000	1,834,000,000	84,000,000	750,000,000
Balance of plant (£)	150,947,310	717,684,619	92,835,137	97,077,145
Heat exchangers (£)	9,000,000	17,500,000	3,500,000	10,000,000
Ancillaries (£)	23,552,748	113,113,432	14,588,117	14,958,118
Building (£)	40,500,000	40,500,000	40,500,000	40,500,000
ATES / BTES (£)	69,600,000	104,400,000	69,600,000	92,800,000
Heat pumps (£)	300,000,000	1,800,000,000	240,000,000	100,000,000
Diurnal storage (£)	158,054,954	444,668,631	39,762,338	183,462,364
Controls (£)	63,062,751	255,413,834	29,919,780	65,715,381
Testing (£)	66,556,388	268,184,526	31,415,769	69,001,150
Water treatment (£)	6,000,000	9,000,000	6,000,000	8,000,000
Sub-total (£)	**1,396,874,150**	**5,631,065,041**	**658,921,140**	**1,448,214,158**
Pre-lims and profit (£)	111,843,334	450,550,003	52,778,491	115,921,933
Fees - design and legals (£)	97,862,917	394,231,253	46,181,180	101,431,691
Project management (£)	69,902,084	281,593,752	32,986,557	72,451,208
TOTAL (£)	**1,676,482,486**	**6,757,440,049**	**790,867,368**	**1,738,018,990**

The figures contained within Table 43 show that the main drivers of CAPEX for the VLTHW system are the pipework and heat pumps.

Table 44 Elemental breakdown of CAPEX for MTHW options

Option	MT – 1A	MT – 1B	MT – 2A	MT – 2B
Distance (kM)	**35**	**130**	**20**	**75**
Pumps (£)	5,800,000	25,800,000	7,400,000	17,800,000
Pipework (£)	360,000,000	1,310,000,000	84,000,000	608,000,000
Balance of plant (£)	89,054,288	228,089,200	39,047,356	118,838,136
Heat exchangers (£)	15,000,000	15,000,000	5,000,000	12,500,000
Ancillaries (£)	14,842,381	38,014,867	6,507,893	19,806,356
Building (£)	40,500,000	40,500,000	40,500,000	40,500,000
ATES / BTES (£)	63,600,000	127,200,000	63,600,000	127,200,000
Heat pumps (£)	-	-	-	-
Diurnal storage (£)	218,637,628	615,487,335	54,847,853	253,817,119
Controls (£)	40,842,215	120,345,070	15,235,655	60,263,581
Testing (£)	42,604,326	126,362,324	15,997,438	63,276,760
Water treatment (£)	3,000,000	6,000,000	3,000,000	6,000,000
Sub-total (£)	**893,880,839**	**2,652,798,795**	**335,136,195**	**1,328,001,951**
Pre-lims and profit (£)	72,045,667	212,288,704	26,875,696	106,304,956
Fees – design and legals (£)	63,039,959	185,752,616	23,516,234	93,016,837
Project management (£)	45,028,542	132,680,440	16,797,310	-
TOTAL (£)	**1,073,995,007**	**3,183,520,555**	**402,325,434**	**1,527,323,744**

The largest single element of CAPEX under the MTHW system is the pipework costs however, when compared against the VLTHW figures it is clear that cost of pipework is much reduced due to the higher temperature differences available.

A graphical representation of the CAPEX breakdown in shown in Figure 103.

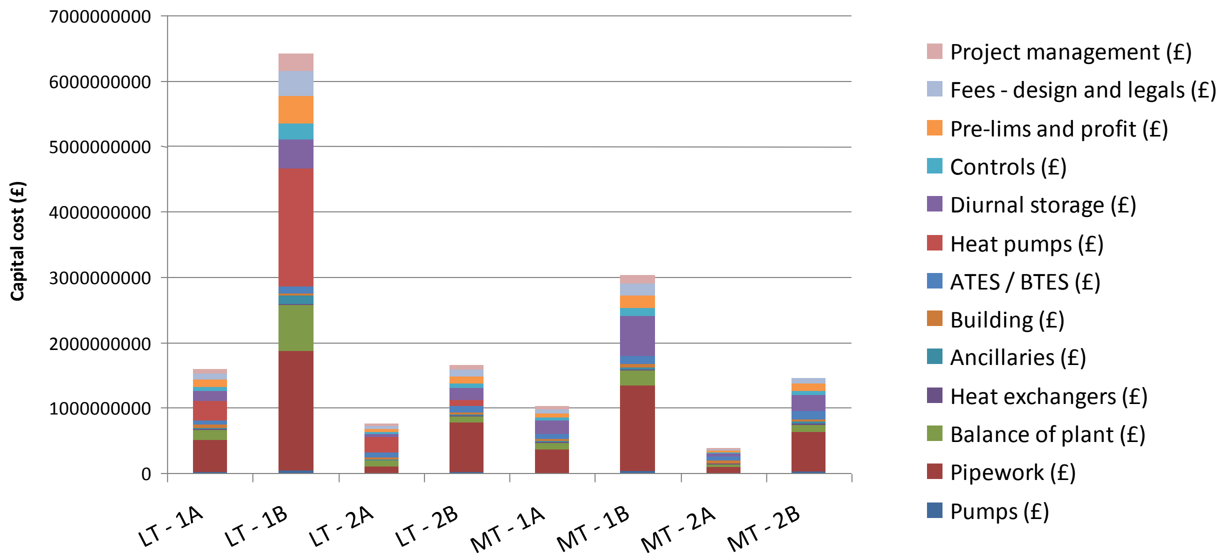

Figure 104 Elemental CAPEX breakdown by option

Section Summary

The following key conclusions are highlighted below.

- As previously discussed, the low temperature system will result in the higher CAPEX this is mostly due to the large cost associated with the large scale heat pumps vs. that of plate heat exchangers
- The options to serve an increased heat network from the Fiddlers ferry power station (options 1b) is proving to be the most expensive options, this is due to the length of the heat networks and associated piping costs

Further considerations

Costs which have not been concluded accounted for include :

- Local distribution network costs
- Land costs

With regards the local distribution network, it is understood that this will be considered in further studies by the ETI.

CAPEX Optimism Bias

Optimism bias is a proven, systematic tendency for project appraisals to be optimistic. HM Treasury issue guidance on how to address this through the use of capital cost uplift factors[14] .For 'non-standard civil engineering' projects a cost uplift of 66% is recommended.

The impact of including optimism bias in the assessments has been allowed for and increases the cost of energy supply by 66% to the figures indicated in Figure 105 below.

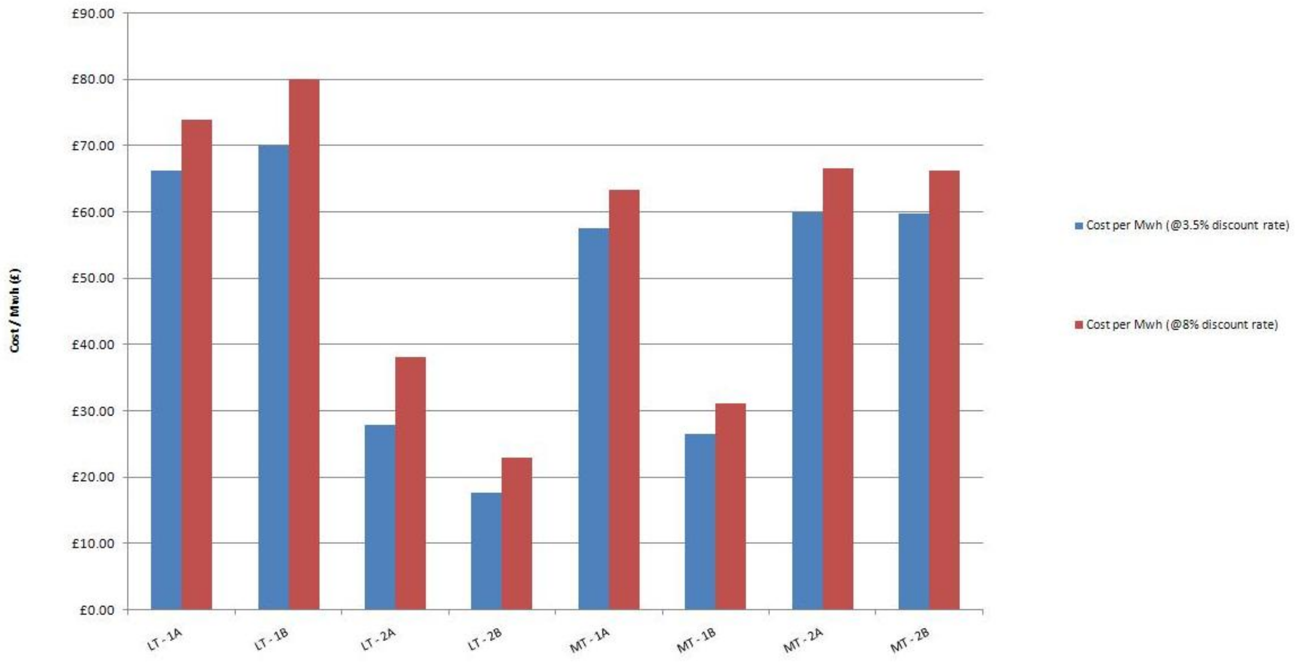

Figure 105 Graph indicating the Cost of Heat including Optimism Bias

In practice as the business case for a project is developed in more detail many of the risks which cause cost uplift can be mitigated. The main strategies for mitigating optimism bias are:

- Full identification of stakeholder requirements (including consultation);
- Accurate costing; and
- Project and risk management.

At the next stage of project development a detailed cost study is recommended, together with consultation involving key stakeholders including energy companies, local authorities, highway authorities, major utilities, regulators and equipment suppliers.

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[14] HM treasury (2011), Supplementary Green Book Guidance – Optimism Bias – Http://www.hm-treasury.gov.uk/d/5(3).pdf

8.3 Example Numerical Modelling

8.3.1 Introduction

Previous simulation results were based on numerical modelling assuming generic assumptions for sandstones in the UK. In order to demonstrate modelling on the basis of more site specific assumptions, a potentially suitable area was chosen to represent a case study site representative of the hydrogeology beneath both Fiddler's Ferry and Hartlepool Power Station. For this area desk study based data and information has been collected as summarised in this section.

8.3.2 The Area

Site geology

The immediate solid geology of the area to which data has been sourced is represented by outcropping formations of the Mercia Mudstone and Jurassic strata (Upper, Middle and Lower) – mainly clays, mudstones and limestones see Figure 106. The geological formations dip eastwards towards the North Sea and are underlain by the Sherwood Sandstone (part of the Permo-Triassic sandstone group) at between approximately 200m and 600m below ground level.

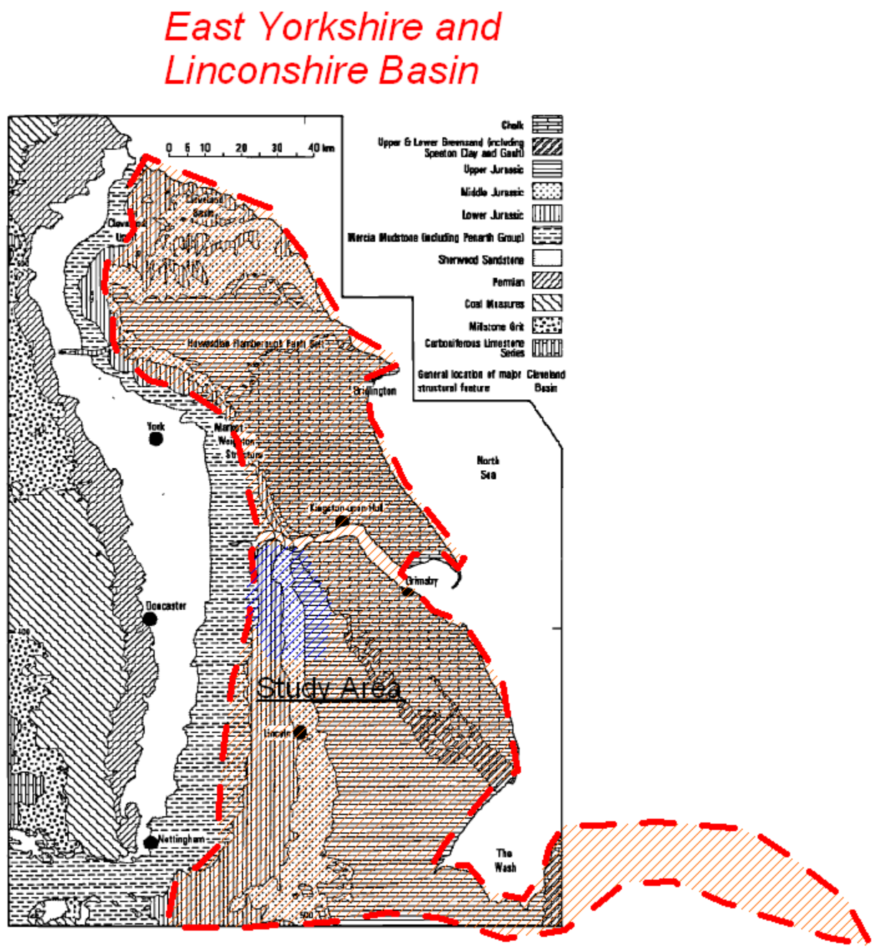


Figure 106: Intermediate solid geology underneath the case study area

8.3.3 Hydrogeology

Near surface hydrogeology

Near the surface formations with significant aquifer formations are the Oolitic and Lincolnshire Inferior Oolite Limestone of Jurassic origin. The Environment Agency groundwater source protection zone maps reveal a number of groundwater source protection zones and associated water abstractions from the Lincolnshire Inferior Oolite.

Hydrogeology at depths (>300m - ~800m)

The geological maps and records of a borehole drilled south of the site, show that these near surface aquifers are underlain by the Mercia Mudstone of approximately 200m in thickness.

Situated underneath the Mercia Mudstones are strata of the Permo-Triassic comprising groups of the Sherwood Sandstone and Permian sandstones.

'Theis analysis' of a pumping test carried out in a water well with 'open section' probably between 220m and 430m revealed a transmissivity of 50m^2/day and a 'storage compressibility' of 5.7x10^{-4}. Dividing by the response zone thickness (210m) the hydraulic conductivity was taken as 0.24m/d (3x10^{-6}m/s). Such rates of permeability are confirmed by Gale et al, stating that hydraulic conductivity are higher at the outcrop areas. However, "*even allowing for the fact that the permeability of the sandstone probably declines towards the east below overlying sediments, the average permeability is still likely to exceed 200mD*" (~0.2m/d) "*and will probably be much higher in particular horizons*". For the purpose of the simulations a groundwater level of approximately 28m below was assumed. However, depending on the specific location and the topography in which the well field is placed, water levels can be shallower suggests a rest water level of approximately 21.4m.

Hydrochemistry

The East Yorkshire and Lincolnshire basins contain water with salinity lower than or equal to sea water. Salinity is expressed as total dissolved solids (TDS) between 5,000mg/l to 50,000mg/l with the lowest concentrations in the west increasing towards the east. This suggests TDS concentrations significantly below that of seawater at the western border of the case study site increasing to the west and also with the depth of the Sherwood Sandstone.

8.3.4 Numerical heat modelling methodology

As for the previous generic examples the Finite Element Subsurface Flow system (FEFLOW) computer program version 5.4 was utilised. A summary of the assumed conceptual model, including model input parameters, entered into the FEFLOW program is given below.

8.3.5 Conceptual model and settings

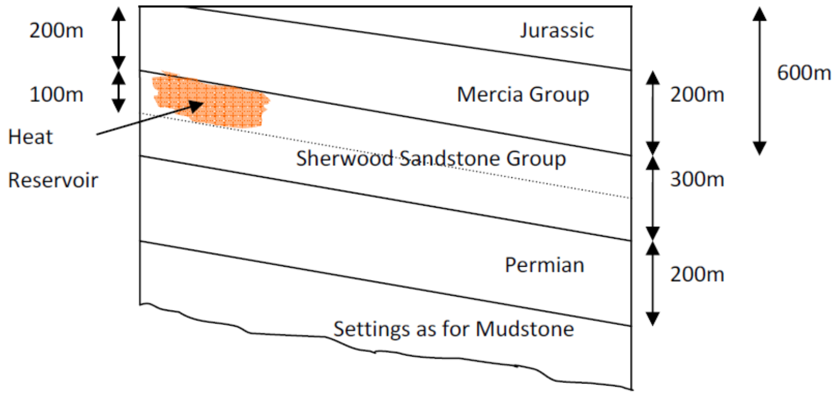


Figure 107 Conceptual model illustrating a sandstone aquifer overlain by Mercia Group

Table 45: Key model input parameters

	Aquifer (Sandstone)	**Overlying aquitard**
Thickness of aquifer unit utilised	100m	100m
Flow specific		
Reference hydraulic conductivity (@20°C) **- horizontal** **- vertical**	3x10^{-6}m/s 1.5x10^{-6}m/s	5 x 10^{-7} m/s 5 x 10^{-7} m/s
Specific storage (storage compressibility)	5.7x10-4	-
Hydraulic gradient	1/500* (set up via constant head boundaries)	-
Heat transport specific		
Initial temperature	20°C	20°C
Thermal conductivity	2.3 W/mK	1.9 W/mK
Volumetric heat capacity (sandstone)	2.05 MJ/m3/K	2.25 MJ/m3/K
Porosity	30%	-
Heat boundary conditions		
At 200mbgl.	-	14°C (constant heat boundary)
Inflowing lateral water flow	20°C (constant heat boundary)	-
Model bottom heat flux	-	50mW/m2 (heat flux)
Reservoir wells	120°C (switched on at times of injection only)	-
Return (outer ring) wells	55°C (switched on at times of injection only)	-

- Not applicable or relevant.
- Whilst no accurate information is currently known to us, at this stage, the hydraulic gradient in such deep aquifers is considered low

8.3.6 Results

Hydraulic Heads

The model was set up allowing an initial 17months reservoir heating/conditioning period. During the 17months reservoir heating/conditioning period a total flow of 10,800m^3/d was facilitated by 24 reservoir wells and 25 return wells.

Heads (especially of 'inner ring' reservoir wells) initially show water levels near ground levels. However, with the reservoir heating up and associated increase in hydraulic conductivities hydraulic heads start to fall (see Figure 108).

After the initial heating/conditioning period, the model was run assuming a 7month abstraction period followed by a 5 month injection period at total flow rates of 17,280m/day. During the optimisation phase, flow rates were modified by lowering the 'outer ring reservoir' (680m^3/d) and proportionally increasing the 'inner ring' reservoir well' (see Figure 109) abstraction rates (800m^3/d) (See also Section 3.2).

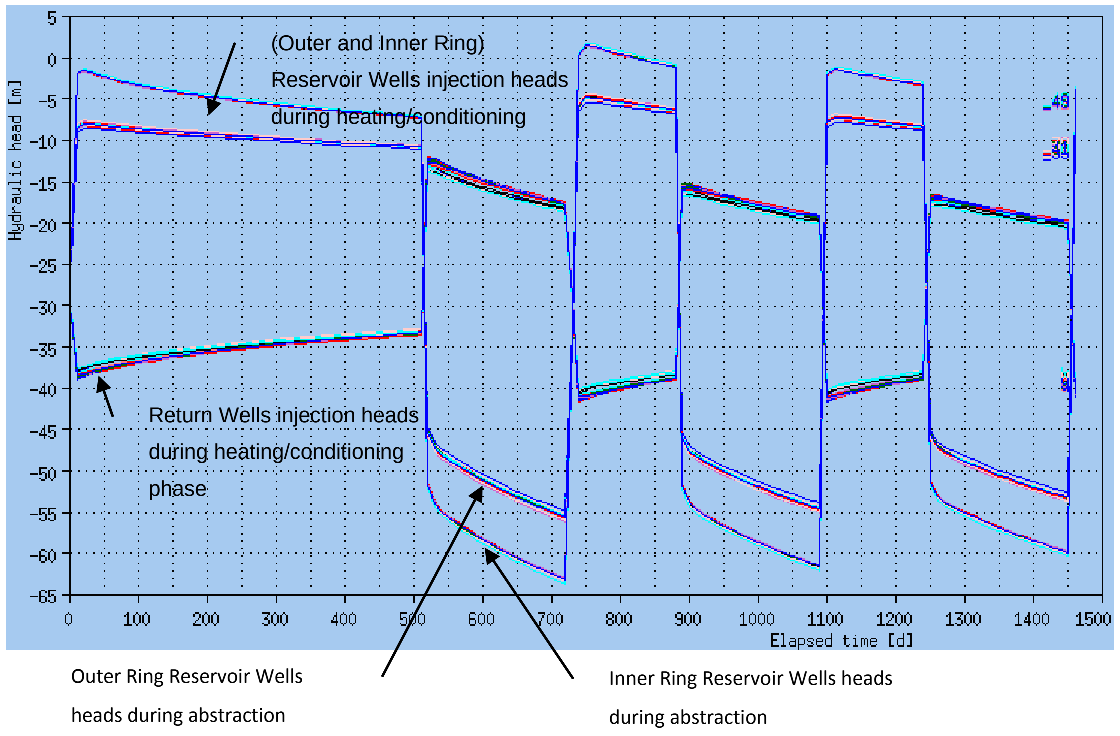


Figure 108: Hydraulic injection and abstraction heads

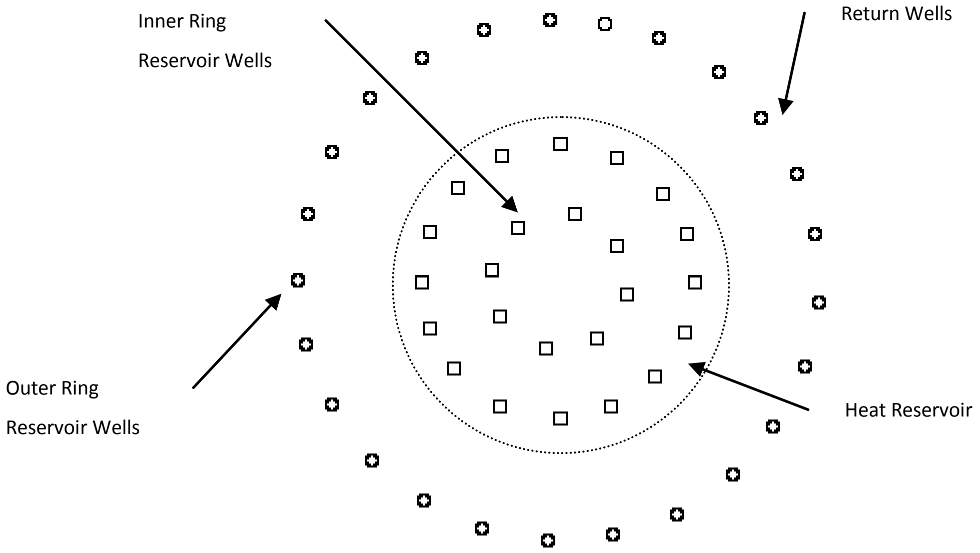
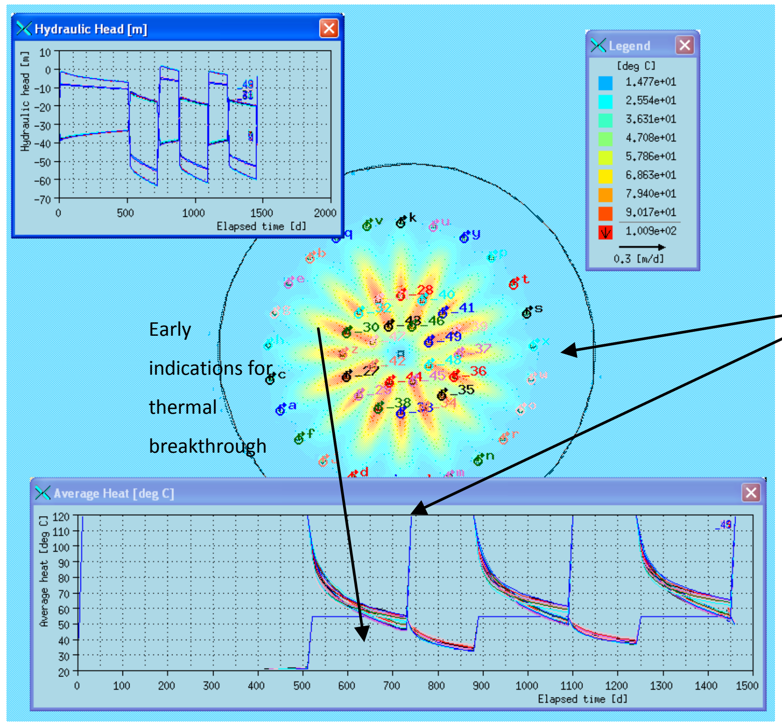


Figure 109: Return and (outer and inner ring) reservoir wells

Trends of heat abstracted/injected

During the end of the 17month heating/conditioning period, the model shows heat plumes to have developed and early indications of thermal breakthrough (the thermal front is starting to reach the Return wells) starting to appear. However, at this stage heat is not uniformly distributed (see Figure 110).

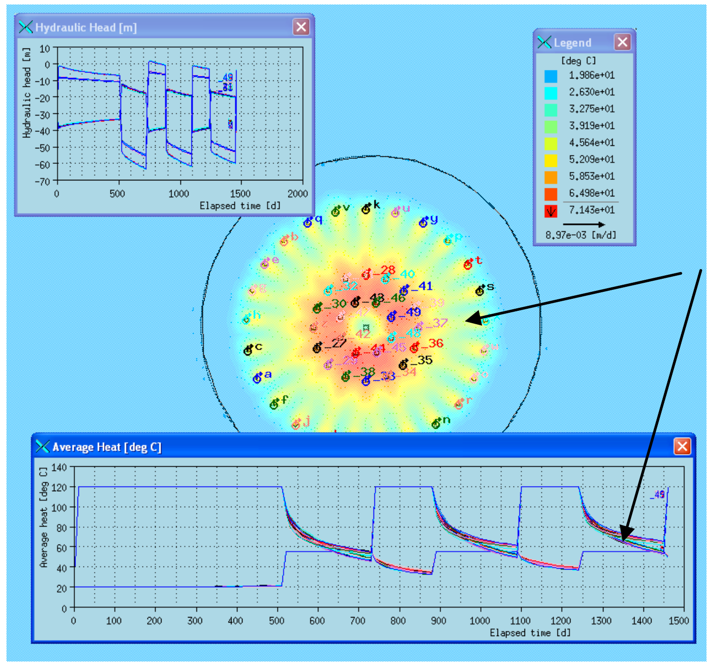


Early indications for thermal breakthrough

End or the 17 months heating period thermo-plot

Figure 110: Temperature plot at the end of the 17months injection period

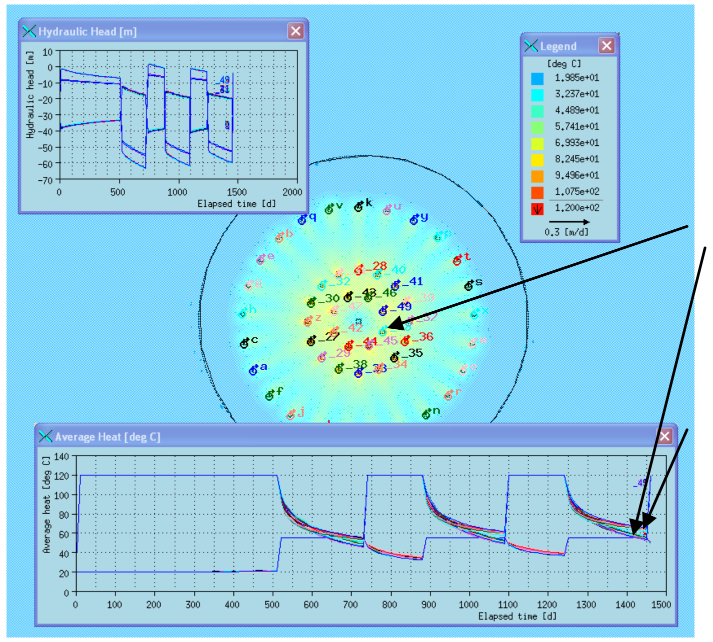
After two abstraction/injection cycles, the model indicates the heat distribution to be more homogenized resulting in higher reservoir efficiencies. A more homogeneous reservoir utilisation was also achieved by lowering the 'outer ring reservoir' (680m^3/d) and proportionally increasing the 'inner ring' reservoir well' abstraction rates (800m^3/d).



Prior to the third heat abstraction thermo-plot

Figure 111: Temperature plot prior to the third abstraction period

The model results suggests that heat is abstracted from reservoir wells at temperatures between 55°C and 65°C at the end of the third abstraction cycle, indicating a good utilisation of the heat reservoir.



Post to the third heat abstraction thermo-plot

Temperatures between 55°C and 65°C

Figure 112: Temperature plot at the end of the third abstraction period

Summary and conclusions

In order to demonstrate modelling on the basis of more site specific assumptions, a potentially suitable area was chosen to represent a case study site. For this study area, data and information has been collected and interpreted.

The information was conceptualised and entered into the FEFLOW computer model. In order to illustrate a possible scenario in which the time required to heat up the reservoir area is reduced the model was set up with an initial 17month heat injection period. Whilst after the 17month time period the model shows early signs of breakthrough the heat is not uniformly distributed and subsequent abstraction/injection cycles will further homogenise the distribution of temperatures in the heat reservoir.

Prior to the third abstraction period, the homogeneity of the reservoir field is improved. In a real system it is considered likely this homogeneity would be an effect of enhanced dispersion/dissemination due to alternating flow directions.

At the end of the third abstraction period temperatures have decreased to 55°C from 65°C. This small variance and drawdown to minimum utilisable temperatures is generally associated with a high utilisation and reservoir efficiency.

Area specific information suggests the salinity, expressed in total dissolved solids (TDS), in the case study area varies between 5,000mg/l to 50,000mg/l. In western parts of the case study site the salinity of waters in the Sherwood Sandstone would be significantly lower than seawater. However, dipping eastwards, the depths of the Sherwood Sandstone and its salinity concentrations increase. With increasing concentrations of salinity a number of fluid specific model parameters (e.g. viscosity, density, thermal conductivity and heat capacity) are subject to change. In this case the model can be adjusted to address any such site or area specific parameters.

9 Geographical Information System (GIS) Analysis

During the project a number of layers were created do further analysis of the potential for geological heat storage in the UK.

To describe the process taken to develop the GIS mapping and complete the Multi-Criteria Analysis a process map is presented in Figure 113. On the left hand side of this diagram there is a list of the various input layers and data sets. These are loosely split into below ground information and power/ energy data. The next step was to interpret these layers to create a set of baseline maps such as deep sandstone, heat density etc. prior to the completion of Multi-Criteria Analysis relating to each MSOA and Power Station. The key denotes the categorisation of each process step.

The different layers are detailed further in section 9.1. The number corresponds with the layer created within the ARCReader file which accompanies this report.

A number of representative GIS maps are shown in section 9.2, as listed below. Chapter 10 provides a description of the calculation process for the multi-criteria analysis.

1. Multi Super Output Area combined Industrial and Domestic Heat Density Demand Map (kWh/m2.annum) based on gas use data
2. Heat Demand Density (HDD) Agglomerations(>30kWh/m2 + Adjacent >10kWh/m2)
3. Medium Super Output Area (MSOA) Multi Criteria Analysis

Power Station MCA to show the effect of increasing the radius from each power station on the potential

4. Power Station Multi Criteria Analysis (MCA) - 10km Radius (including Agglomerated Heat Demand Density and Deep Sandstone Aquifer)
5. Power Station Multi Criteria Analysis (MCA) - 25km Radius (including Agglomerated Heat Demand Density and Deep Sandstone Aquifer)
6. Power Station Multi Criteria Analysis (MCA) - 50km Radius (including Agglomerated Heat Demand Density and Deep Sandstone Aquifer)
7. Power Station Multi Criteria Analysis (MCA) - 100km Radius (including Agglomerated Heat Demand Density and Deep Sandstone Aquifer)

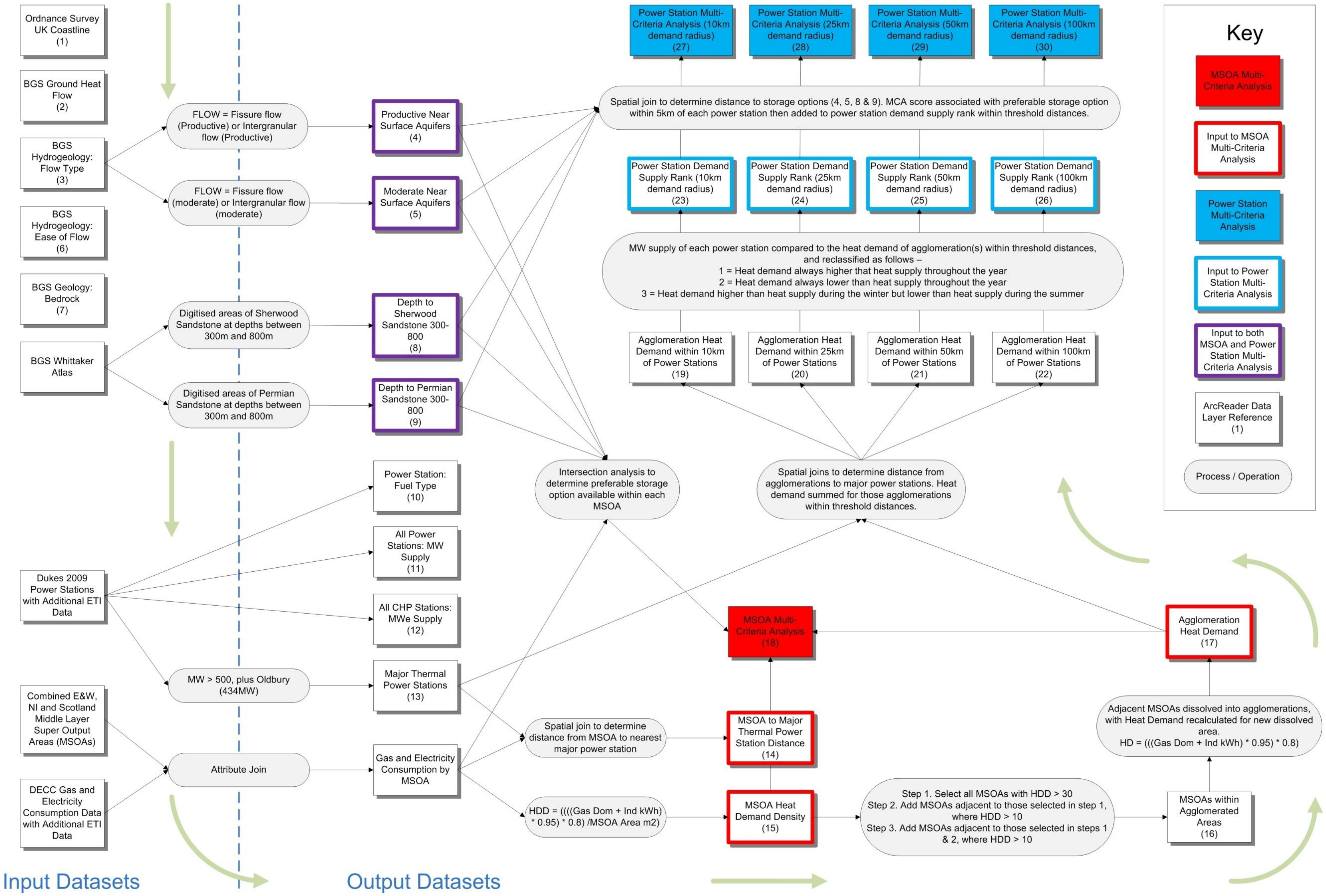


Figure 113 ArcReader Data Layers and Multi Criteria Analysis Methodology (process map from left to right)

9.1 ArcReader - Data Layer Descriptions

1. **Coastline –** UK Coastline Boundary
2. **Ground Heat Flow** – Shows heat flow within rocks. Not used for further analysis.
3. **Hydrogeology: Flow Type –** Shows flow type through rocks, attributes exported to form layers 4 and 5.
4. **Productive Near Surface Aquifers** – Layer exported from layer 3. Includes productive inter-granular flow and fissure flow. Used to calculate areas suitable for LT ATES storage high potential (all MSOAs that intercept these areas of hydrogeology that don't intercept areas covered by 8 or 9 (which represent more productive storage options).
5. **Moderate Near Surface Aquifers** – Layer exported from layer 3. Included moderate inter-granular flow and fissure flow. Used to calculate areas suitable for LT ATES storage medium potential (all MSOAs that intercept these areas of hydrogeology that do not intercept areas covered by 4, 8 or 9).
6. **Hydrogeology: Ease of Flow** – Shows ease of flow through rocks. Not used for further analysis.
7. **Geology: Bedrock -** Shows bedrock type. Not used for further analysis.
8. **Depth to Sherwood Sandstone 300-800m** – Layer digitised from .pdf. Represents deep Sherwood Sandstone at depths of between 300 and 800 metres. Used to calculate areas suitable for MT ATES (all MSOAs that intercept these areas of hydrogeology).
9. **Depth to Permian Sandstone 300-800m** – Layer digitised from .pdf. Represents deep Permian Sandstone at depths of between 300 and 800 metres. Used to calculate areas suitable for MT ATES (all MSOAs that intercept these areas of hydrogeology).
10. **Power Station: Fuel Type** – All power stations in the UK identified by fuel type.
11. **All Power Stations: MW Supply** – All power stations in the UK identified by MWe capacity.
12. **All CHP Stations MWe Supply** – All CHP Stations in the UK identified by MWe capacity.
13. **Major Thermal Power Stations** – All power stations in the UK with a MW capacity greater than 500 (also includes Oldbury at 434MW). Used to calculate layer 14.
14. **MSOA to major thermal power station distance** – Shows the distance in KM from each MSOA to the nearest major power station as defined by layer 13. This data is used within the MSOA Multi Criteria Analysis.
15. **MSOA Heat Demand Density** – Calculated from Domestic and Industrial kWh demand data. These were multiplied by 0.95 to establish estimate of gas use for heat, and multiplied by 0.8 to factor in plant efficiency. This gave Heat Demand, which was divided by area of each MSOA in metres to give heat demand density (HDD). HDD = ((((Gas Dom + Ind kWh) * 0.95) *0.8) / MSOA Area m^2)
16. **MSOAs within Agglomerated Areas** – Layer to demonstrate agglomeration areas, with the ability to see which MSOAs make up the agglomerations, i.e. those areas with the strongest economic vaiability for district heating. All MSOAs with a heat demand density (as defined within layer 15) over 30kWh/m^2.annum were initially selected. All adjacent MSOAs with a heat demand density greater than 10 were then attached. Finally all adjacent MSOAs with a heat demand density greater than 10 were attached for a second time. ((HHD >30 + adjoining HDD > 10) + adjoining HDD > 10).
17. **Agglomeration Heat Demand** – Layer was created as an additional proxy / category for the MSOA Multi Criteria Analysis. All MSOAs within agglomerated areas were dissolved into agglomeration units. Previous domestic gas and industrial data was re-linked with the layer and heat demand was re-calculated for the agglomeration HD = (((Gas Dom + Ind kWh) *0.95) *0.8). The allocation of MSOA suitability rating depending on the Heat Demand of the agglomeration it falls within is discussed below.
18. **MSOA Multi Criteria Analysis –** This was established using different suitability parameters within 4 categories. Reference should be made to the MSOA Multi Criteria Analysis description for further details. Click on each MSOA for a summary of rank breakdown.
19. **Agglomeration Heat Demand within 10km of Power Station** – Layer provides an input to the Power Station Multi Criteria Analysis at a 10km radius. The Heat Demand of the agglomerations (17) within 10km of the major thermal power stations (13) was summed. Suitability thresholds in were set with reference to power station supply and forms layer 23.
20. **Agglomeration Heat Demand within 25km of Power Station** - Layer provides an input to the Power Station Multi Criteria Analysis at a 10km radius. The Heat Demand of the agglomerations (17) within 25km of the major thermal power stations (13) was summed. Suitability thresholds in were set with reference to power station supply and forms layer 24.
21. **Agglomeration Heat Demand within 50km of Power Station -** Layer provides an input to the Power Station Multi Criteria Analysis at a 10km radius. The Heat Demand of the agglomerations (17) within 50km of the major thermal power stations (13) was summed. Suitability thresholds in were set with reference to power station supply and forms layer 25.
22. **Agglomeration Heat Demand within 100km of Power Station** – Layer provides an input to the Power Station Multi Criteria Analysis at a 10km radius. The Heat Demand of the agglomerations (17) within 100km of the major thermal power stations (13) was summed. Suitability thresholds in were set with reference to power station supply and forms layer 26.
23. **Power Station Demand Supply Rank (10km demand radius)** – The MW supply of each power station was related to the agglomeration Heat Demand within 10km (19). The formula for which is described within the Power Station MCA section. Three values were given 1 = Heat Demand always higher than Heat Supply throughout the year, 2 = Heat Demand always lower than Heat Supply throughout the year, 3 = Heat Demand higher than Heat Supply in the winter but lower than Heat Supply during the summer.
24. **Power Station Demand Supply Rank (25km demand radius)** – The MW supply of each power station was related to the agglomeration Heat Demand within 25km (20). The formula for which is described within the Power Station MCA section. Three values were given 1 = Heat Demand always higher than Heat Supply throughout the year, 2 = Heat Demand always lower than Heat Supply throughout the year, 3 = Heat Demand higher than Heat Supply in the winter but lower than Heat Supply during the summer.
25. **Power Station Demand Supply Rank (50km demand radius)** – The MW supply of each power station was related to the agglomeration Heat Demand within 50km (21). The formula for which is described within the Power Station MCA section. Three values were given 1 = Heat Demand always higher than Heat Supply throughout the year, 2 = Heat Demand always lower than Heat Supply throughout the year, 3 = Heat Demand higher than Heat Supply in the winter but lower than Heat Supply during the summer.
26. **Power Station Demand Supply Rank (100km demand radius)** – The MW supply of each power station was related to the agglomeration Heat Demand within 100km (22). The formula for which is described within the Power Station MCA section. Three values were given 1 = Heat Demand always higher than Heat Supply throughout the year, 2 = Heat Demand always lower than Heat Supply throughout the year, 3 = Heat Demand higher than Heat Supply in the winter but lower than Heat Supply during the summer.
27. **Power Station Multi Criteria Analysis (10km demand radius)** – The value given when the MCA criteria associated with each power station is summed, including threshold ranks associated with agglomeration Heat Demand within 10km. Refer to Power Station MCA Section. Click on each power Station for a summary of rank breakdown.
28. **Power Station Multi Criteria Analysis (25km demand radius)** – The value given when the MCA criteria associated with each power station is summed, including threshold ranks associated with agglomeration Heat Demand within 25km. Refer to Power Station MCA Section. Click on each power Station for a summary of rank breakdown.
29. **Power Station Multi Criteria Analysis (50km demand radius)** – The value given when the MCA criteria associated with each power station is summed, including threshold ranks associated with agglomeration Heat Demand within 50km. Refer to Power Station MCA Section. Click on each power Station for a summary of rank breakdown.
30. **Power Station Multi Criteria Analysis (100km demand radius)** – The value given when the MCA criteria associated with each power station is summed, including threshold ranks associated with agglomeration Heat Demand within 100km. Refer to Power Station MCA Section. Click on each power Station for a summary of rank breakdown.

9.2 Example GIS Maps

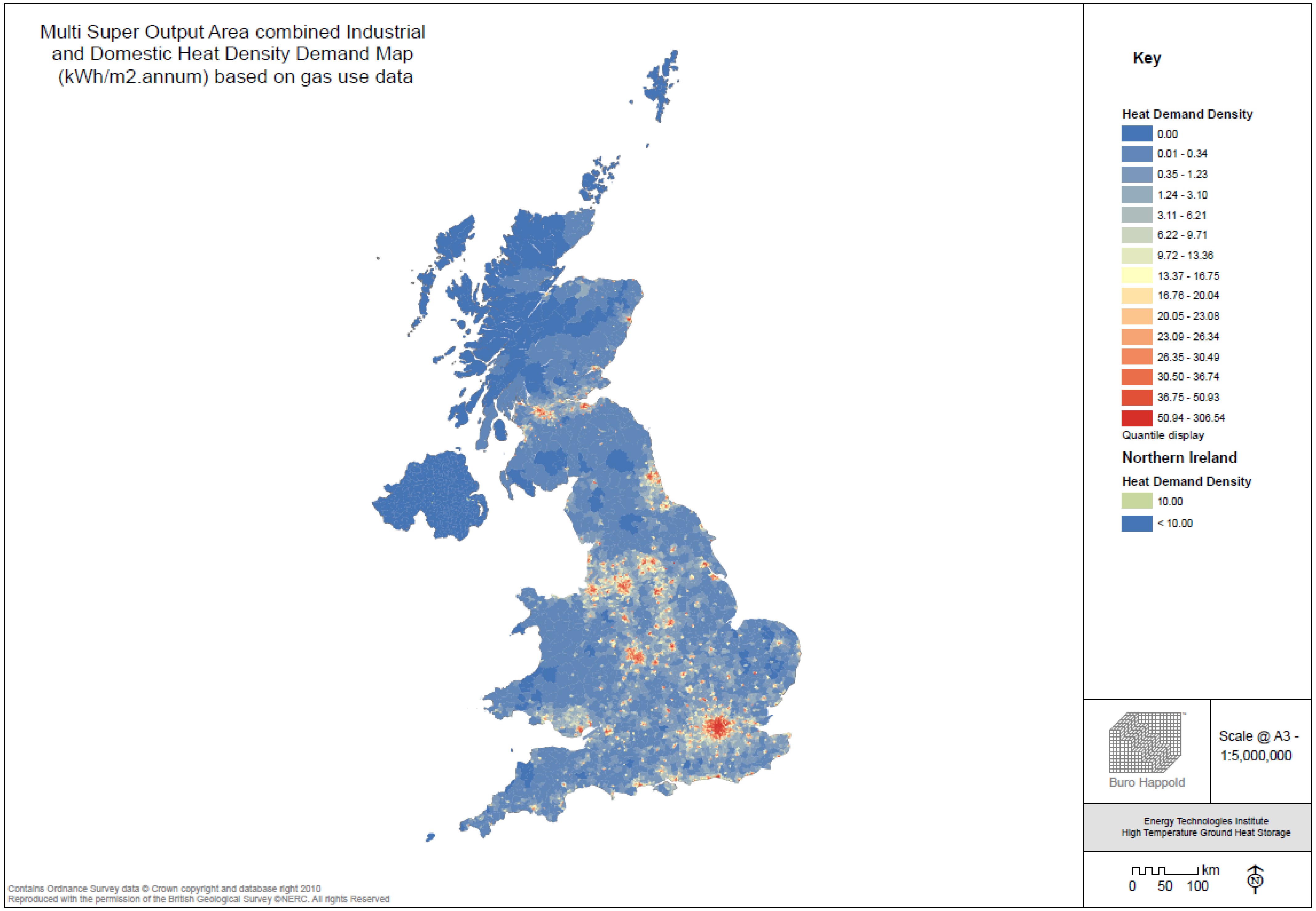


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Figure 114 Multi Super Output Area combined Industrial and Domestic Heat Density Demand Map (kWh/m2.annum)

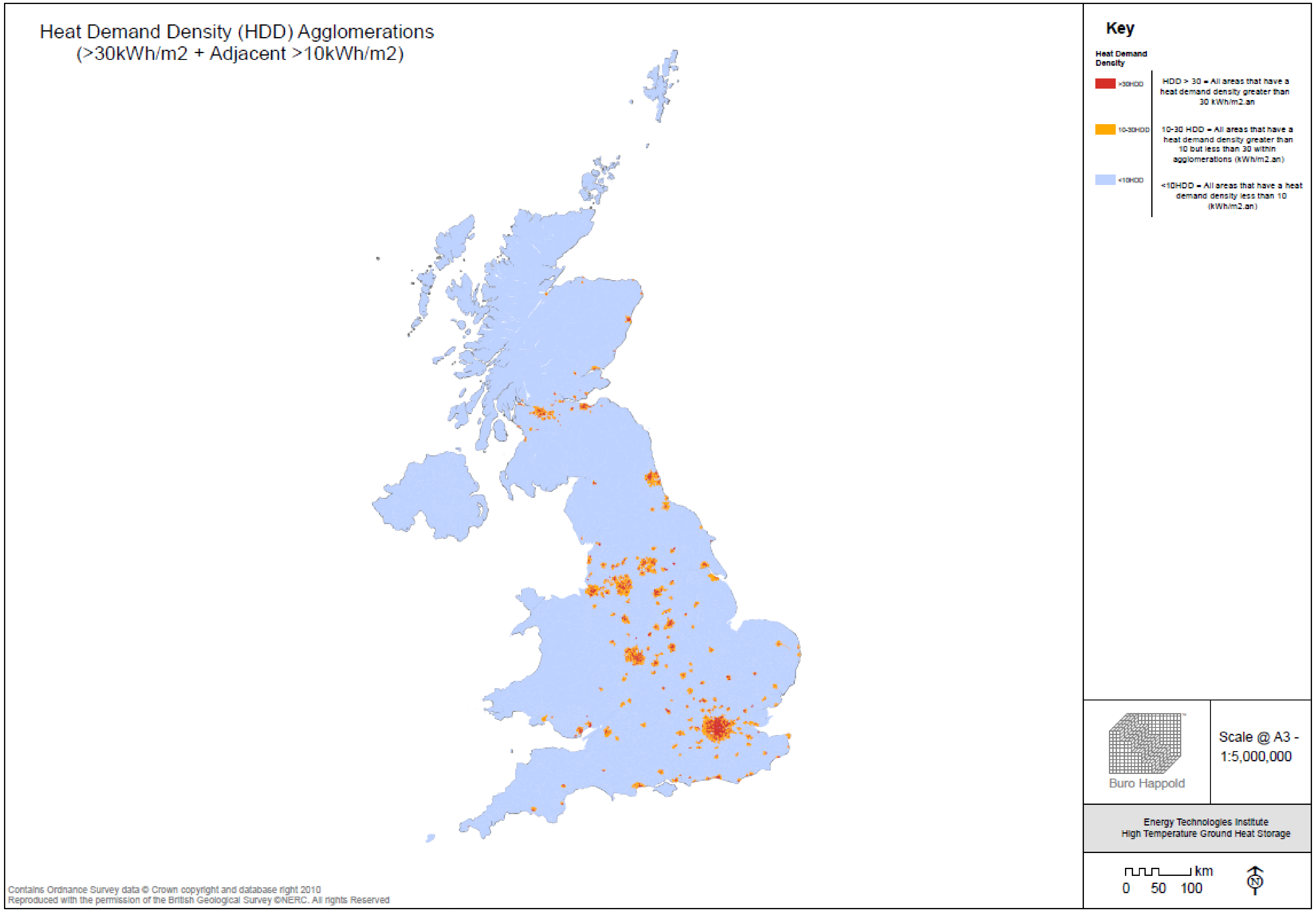

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Figure 115 Heat Demand Density (HDD) Agglomerations(>30kWh/m^2 + Adjacent >10kWh/m^2)

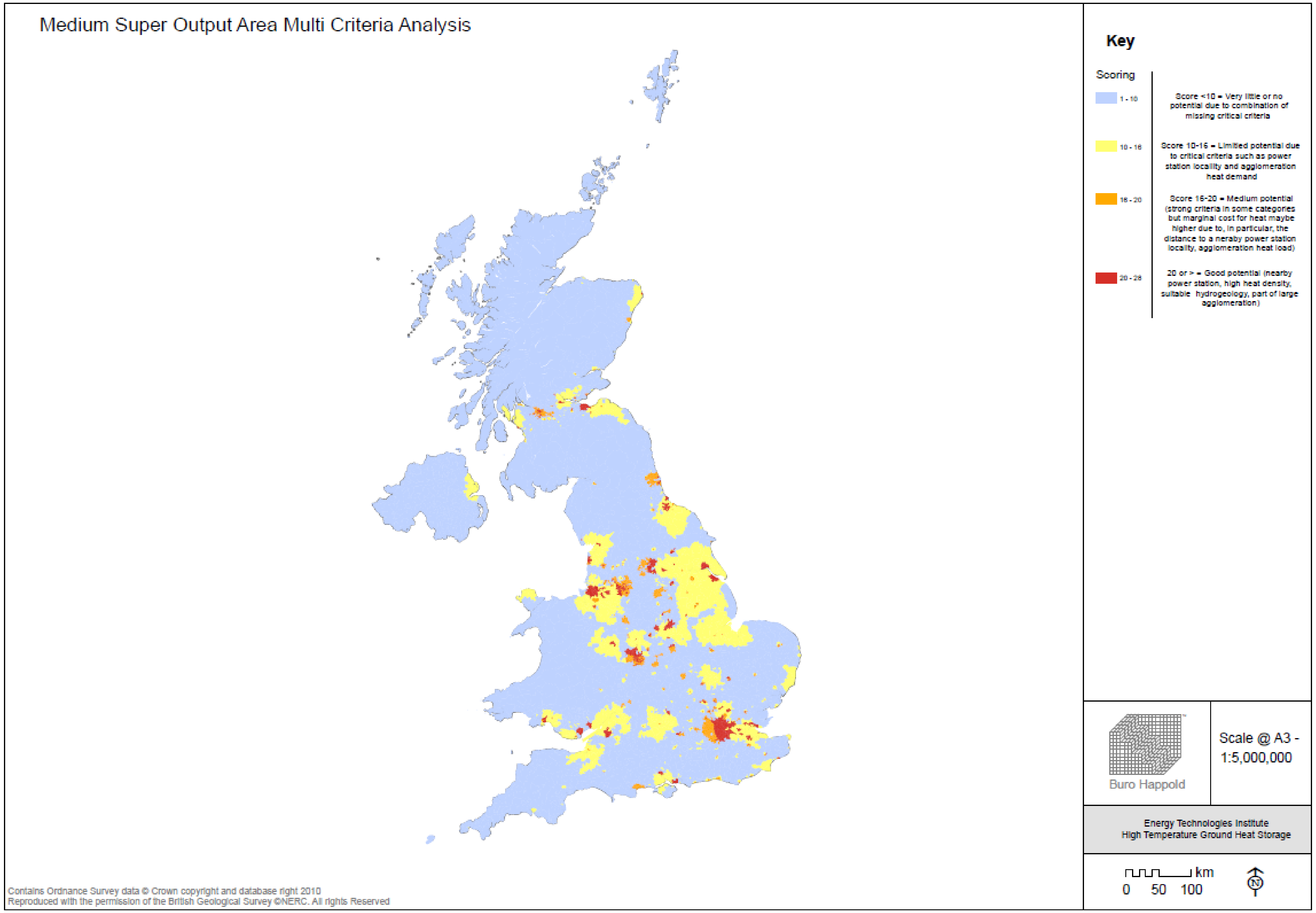

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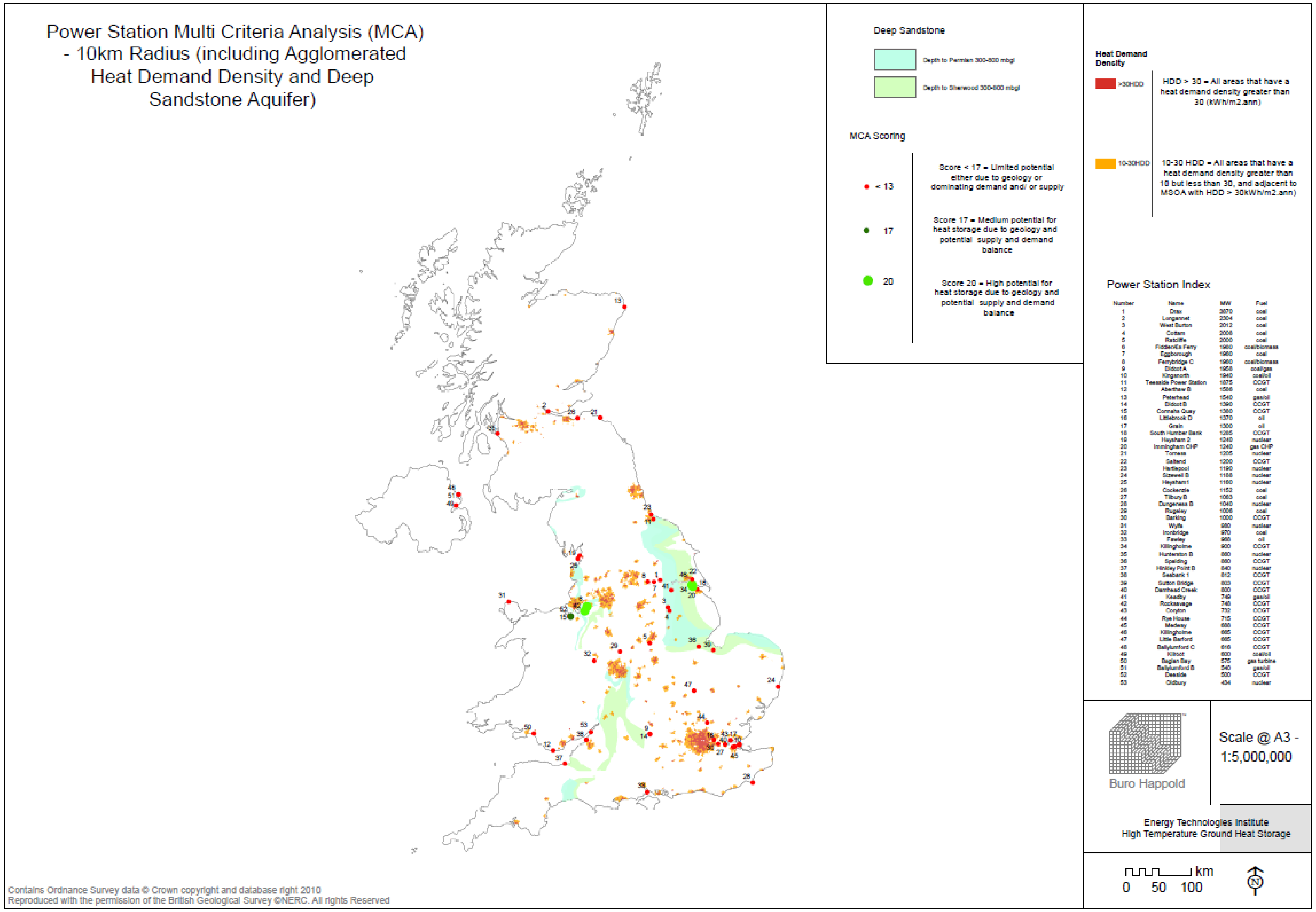
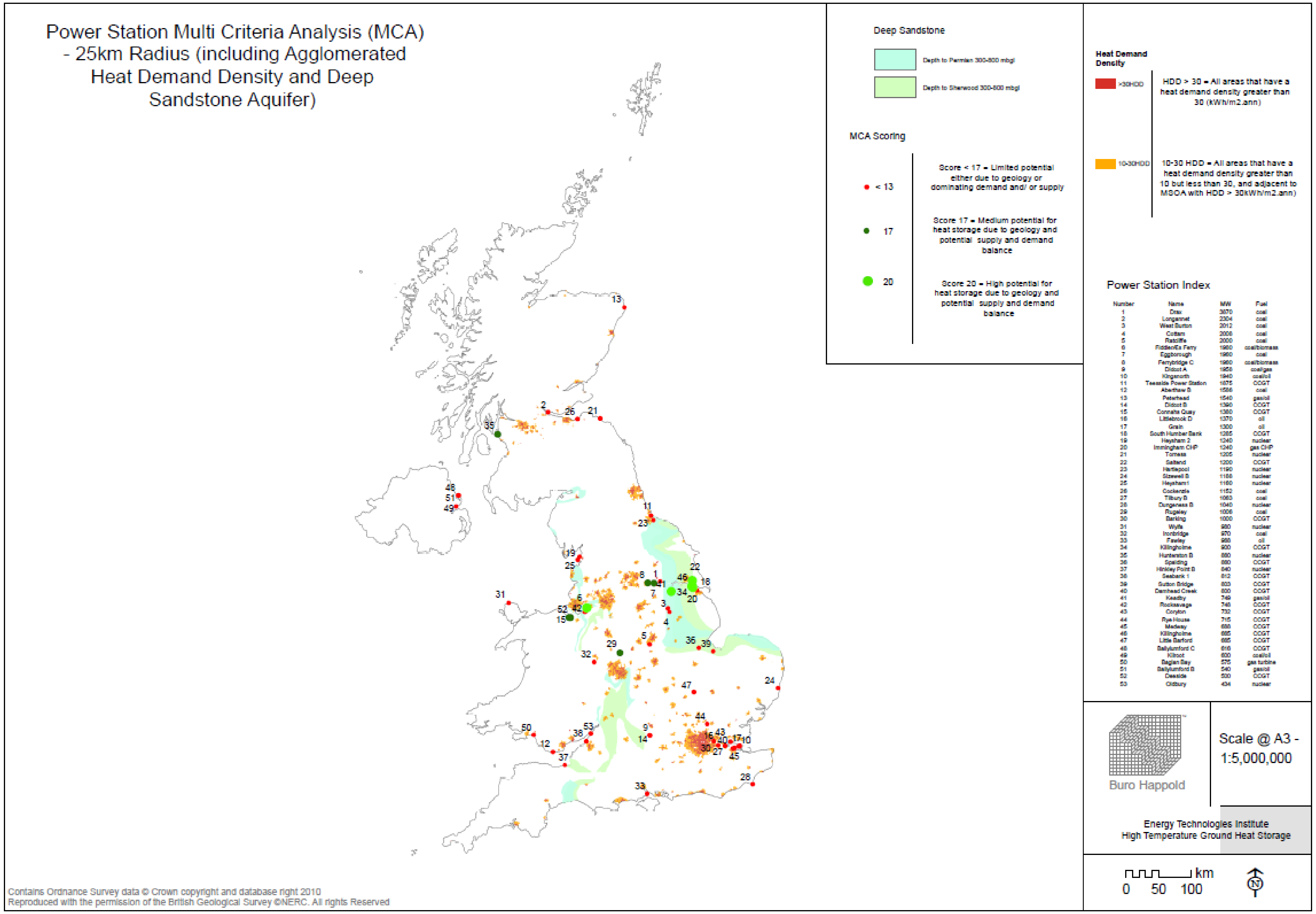
Figure 116 Medium Super Output Area (MSOA) Multi Criteria Analysis



Power Station Index

Number	Name	MW	Fuel
1	Drax	3870	coal
2	Longannet	2304	coal
3	West Burton	2012	coal
4	Cottam	2008	coal
5	Ratcliffe	2000	coal
6	Fiddler's Ferry	1980	coal/biomass
7	Eggborough	1960	coal
8	Ferrybridge C	1960	coal/biomass
9	Didcot A	1958	coal/gas
10	Kingsnorth	1940	coal/oil
11	Teesside Power Station	1875	CCGT
12	Aberthaw B	1586	coal
13	Peterhead	1540	gas/oil
14	Didcot B	1390	CCGT
15	Connahs Quay	1380	CCGT
16	Littlebrook D	1370	oil
17	Grain	1300	oil
18	South Humber Bank	1285	CCGT
19	Heysham 2	1240	nuclear
20	Immingham CHP	1240	gas CHP
21	Torness	1205	nuclear
22	Saltend	1200	CCGT
23	Hartlepool	1190	nuclear
24	Sizewell B	1188	nuclear
25	Heysham 1	1160	nuclear
26	Cockenzie	1152	coal
27	Tilbury B	1063	coal
28	Dungeness B	1040	nuclear
29	Rugeley	1006	coal
30	Barking	1000	CCGT
31	Wylfa	980	nuclear
32	Ironbridge	970	coal
33	Fawley	968	oil
34	Killingholme	900	CCGT
35	Hunterston B	880	nuclear
36	Spalding	880	CCGT
37	Hinkley Point B	840	nuclear
38	Seabank 1	812	CCGT
39	Sutton Bridge	803	CCGT
40	Damhead Creek	800	CCGT
41	Keadby	749	gas/oil
42	Rocksavage	748	CCGT
43	Coryton	732	CCGT
44	Rye House	715	CCGT
45	Medway	688	CCGT
46	Killingholme	665	CCGT
47	Little Barford	665	CCGT
48	Ballylumford C	616	CCGT
49	Kilroot	600	coal/oil
50	Baglan Bay	575	gas turbine
51	Ballylumford B	540	gas/oil
52	Deeside	500	CCGT
53	Oldbury	434	nuclear

Figure 117 Power Station Multi Criteria Analysis (MCA) - 10km Radius



Power Station Multi Criteria Analysis (MCA) - 25km Radius (including Agglomerated Heat Demand Density and Deep Sandstone Aquifer)

Deep Sandstone

- 🟦 Depth to Permian 300-800 mbgl
- 🟩 Depth to Sherwood 300-800 mbgl

MCA Scoring

● < 13	Score < 17 = Limited potential either due to geology or dominating demand and/ or supply
● 17	Score 17 = Medium potential for heat storage due to geology and potential supply and demand balance
● 20	Score 20 = High potential for heat storage due to geology and potential supply and demand balance

Heat Demand Density

🟥 >30HDD	HDD > 30 = All areas that have a heat demand density greater than 30 (kWh/m2.ann)
🟧 10-30HDD	10-30 HDD = All areas that have a heat demand density greater than 10 but less than 30, and adjacent to MSOA with HDD > 30kWh/m2.ann)

Power Station Index

Number	Name	MW	Fuel
1	Drax	3870	coal
2	Longannet	2304	coal
3	West Burton	2012	coal
4	Cottam	2008	coal
5	Ratcliffe	2000	coal
6	Fiddler's Ferry	1980	coal/biomass
7	Eggborough	1960	coal
8	Ferrybridge C	1960	coal/biomass
9	Didcot A	1958	coal/gas
10	Kingsnorth	1940	coal/oil
11	Teesside Power Station	1875	CCGT
12	Aberthaw B	1586	coal
13	Peterhead	1540	gas/oil
14	Didcot B	1390	CCGT
15	Connahs Quay	1380	CCGT
16	Littlebrook D	1370	oil
17	Grain	1300	oil
18	South Humber Bank	1285	CCGT
19	Heysham 2	1240	nuclear
20	Immingham CHP	1240	gas CHP
21	Torness	1205	nuclear
22	Saltend	1200	CCGT
23	Hartlepool	1190	nuclear
24	Sizewell B	1188	nuclear
25	Heysham I	1160	nuclear
26	Cockenzie	1152	coal
27	Tilbury B	1063	coal
28	Dungeness B	1040	nuclear
29	Rugeley	1006	coal
30	Barking	1000	CCGT
31	Wylfa	980	nuclear
32	Ironbridge	970	coal
33	Fawley	968	oil
34	Killingholme	900	CCGT
35	Hunterston B	880	nuclear
36	Spalding	880	CCGT
37	Hinkley Point B	840	nuclear
38	Seabank 1	812	CCGT
39	Sutton Bridge	803	CCGT
40	Damhead Creek	800	CCGT
41	Keadby	749	gas/oil
42	Rocksavage	748	CCGT
43	Coryton	732	CCGT
44	Rye House	715	CCGT
45	Medway	688	CCGT
46	Killingholme	665	CCGT
47	Little Barford	665	CCGT
48	Ballylumford C	616	CCGT
49	Kilroot	600	coal/oil
50	Baglan Bay	575	gas turbine
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52	Deeside	500	CCGT
53	Oldbury	434	nuclear

Buro Happold

Scale @ A3 - 1:5,000,000

Energy Technologies Institute
High Temperature Ground Heat Storage

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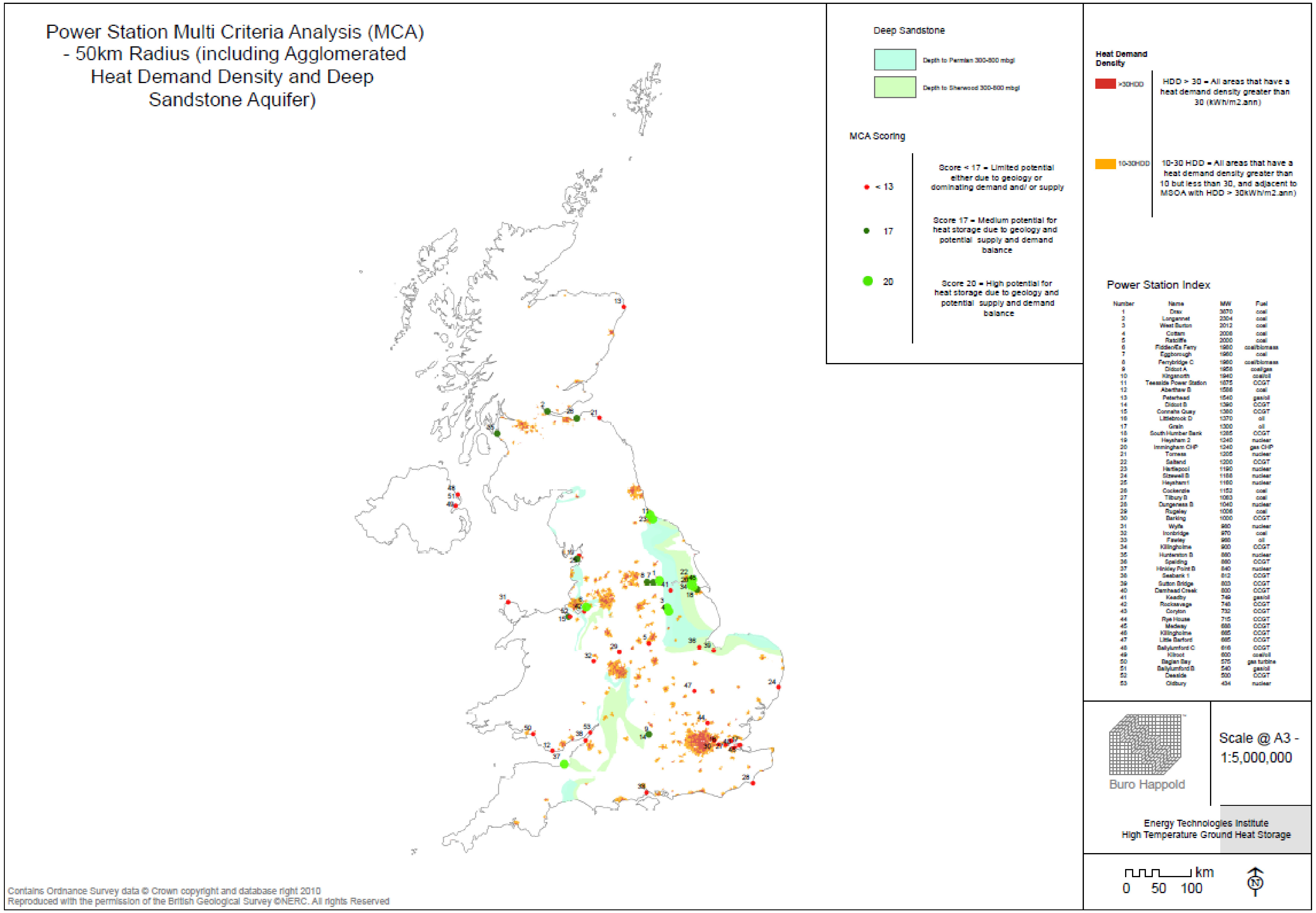
Figure 118 Power Station Multi Criteria Analysis (MCA) - 25km Radius



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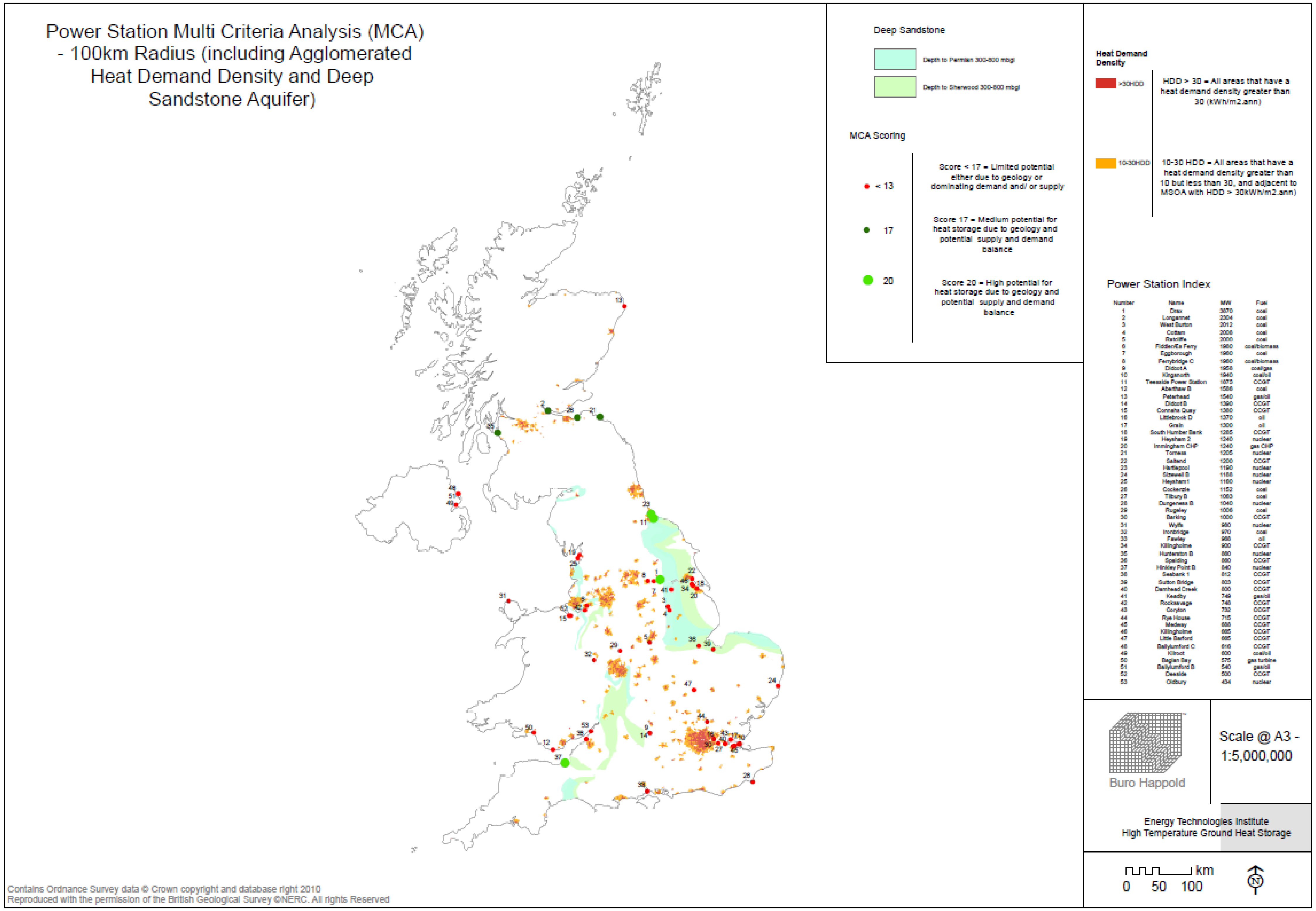
8	Ferrybridge C	1960	coal/biomass
9	Didcot A	1958	coal/gas
10	Kingsnorth	1940	coal/oil
11	Teesside Power Station	1875	CCGT
12	Aberthaw B	1586	coal
13	Peterhead	1540	gas/oil
14	Didcot B	1390	CCGT
15	Connahs Quay	1380	CCGT
16	Littlebrook D	1370	oil
17	Grain	1300	oil
18	South Humber Bank	1285	CCGT
19	Heysham 2	1240	nuclear
20	Immingham CHP	1240	gas CHP
21	Torness	1205	nuclear
22	Saltend	1200	CCGT
23	Hartlepool	1190	nuclear
24	Sizewell B	1188	nuclear
25	Heysham 1	1160	nuclear
26	Cockenzie	1152	coal
27	Tilbury B	1063	coal
28	Dungeness B	1040	nuclear
29	Rugeley	1006	coal
30	Barking	1000	CCGT
31	Wylfa	980	nuclear
32	Ironbridge	970	coal
33	Fawley	968	oil
34	Killingholme	900	CCGT
35	Hunterston B	880	nuclear
36	Spalding	880	CCGT
37	Hinkley Point B	840	nuclear
38	Seabank 1	812	CCGT
39	Sutton Bridge	803	CCGT
40	Damhead Creek	800	CCGT
41	Keadby	749	gas/oil
42	Rocksavage	748	CCGT
43	Coryton	732	CCGT
44	Rye House	715	CCGT
45	Medway	688	CCGT
46	Killingholme	665	CCGT
47	Little Barford	665	CCGT
48	Ballylumford C	616	CCGT
49	Kilroot	600	coal/oil
50	Baglan Bay	575	gas turbine
51	Ballylumford B	540	gas/oil
52	Deeside	500	CCGT
53	Oldbury	434	nuclear

Figure 119 Power Station Multi Criteria Analysis (MCA) - 50km Radius



Power Station Index

Number	Name	MW	Fuel
1	Drax	3870	coal
2	Longannet	2304	coal
3	West Burton	2012	coal
4	Cottam	2008	coal
5	Ratcliffe	2000	coal
6	Fiddler's Ferry	1980	coal/biomass
7	Eggborough	1960	coal
8	Ferrybridge C	1960	coal/biomass
9	Didcot A	1958	coal/gas
10	Kingsnorth	1940	coal/oil
11	Teesside Power Station	1875	CCGT
12	Aberthaw B	1586	coal
13	Peterhead	1540	gas/oil
14	Didcot B	1390	CCGT
15	Connah's Quay	1380	CCGT
16	Littlebrook D	1370	oil
17	Grain	1300	oil
18	South Humber Bank	1285	CCGT
19	Heysham 2	1240	nuclear
20	Immingham CHP	1240	gas CHP
21	Torness	1205	nuclear
22	Saltend	1200	CCGT
23	Hartlepool	1190	nuclear
24	Sizewell B	1188	nuclear
25	Heysham 1	1160	nuclear
26	Cockenzie	1152	coal
27	Tilbury B	1063	coal
28	Dungeness B	1040	nuclear
29	Rugeley	1006	coal
30	Barking	1000	CCGT
31	Wylfa	980	nuclear
32	Ironbridge	970	coal
33	Fawley	968	oil
34	Killingholme	900	CCGT
35	Hunterston B	890	nuclear
36	Spalding	880	CCGT
37	Hinkley Point B	840	nuclear
38	Seabank 1	812	CCGT
39	Sutton Bridge	803	CCGT
40	Damhead Creek	800	CCGT
41	Keadby	749	gas/oil
42	Rocksavage	748	CCGT
43	Coryton	732	CCGT
44	Rye House	715	CCGT
45	Medway	688	CCGT
46	Killingholme	665	CCGT
47	Little Barford	665	CCGT
48	Ballylumford C	616	CCGT
49	Kilroot	600	coal/oil
50	Baglan Bay	575	gas turbine
51	Ballylumford B	540	gas/oil
52	Deeside	500	CCGT
53	Oldbury	434	nuclear

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Figure 120 Power Station Multi Criteria Analysis (MCA) - 100km Radius

10 Potential Estimation – Multi-Criteria Analysis (MCA)

10.1 Confirmation of Parameters used for the Analysis and MCA Normalisation

10.1.1 District by District Review

A spatial review of the UK has been completed by considering the following for each MSOA district

1. Heat Demand and Density
2. Power Station Proximity
3. Geological Heat Storage Option

The purpose of this review is to primarily analyse those districts that are most suited to connection to a heat network connected to a nearby power station. The potential for storage is still considered but as will become apparent in the next section has a relative lower importance than other key criteria as large scale seasonal storage is assumed to be generally be more appropriate adjacent to the power station.

Heat Demand and Density Calculations

The heat demand for each district has been calculated using the following base formula.

$(G_{IDC}+G_{DOM}) \times HF \times E$

Where:

G_{IDC}= [kWh] = Gas used by industrial and commercial property

G_{DOM} = [kWh] = Gas used by domestic consumers

HF = 0.95 = Heat Factor, i.e. proportion of gas used for LTHW heating and not MTHW, process heat, CHP and/ or catering

E = 0.8 = Average Efficiency of heating plant

The heat density has been simply calculated using the area for the respective MSOA and is shown in Appendix C.

It is accepted that the gas heating fraction may vary for certain areas, especially in MSOA where heavy industry is predominant and a high proportion is utilised for high temperature process, and/ or CHP. However, for the basis of this spatial study an average factor for the UK is considered acceptable prior to more detailed studies for individual districts.

For this study the calculation on “heat demand” for each district has then been made by focussing on higher heat density areas where the feasibility of district heating is “economic” rather than the entire UK as previous studies have considered, e.g. James P.A.B and Bahaj J. (2009)

Previously identified thresholds to realise economic viability for district heating are as follows:

- 15kWh/m2 minimum level as used in Scandinavia - needs special low density design, twin pipe etc
- 30kWh/m2 practical level in the UK
- 50kWh/m2 - practical limit of 'core heat density' areas

Thresholds used for study:

Core Heat Density Areas - 30kWh/m2

Adjacent lower density areas - 10kWh/m2*

*lower value used to Scandinavian minimum as perceived economics will change over the coming decades as the study is considering large scale infrastructure changes that will take considerable time to implement.

The resulting Heat Density Map showing the created agglomerations is shown in the previous chapter.

Geological Storage Option Review

The potential for local storage has also been assessed for each district. This has been completed by ranking each district according to the geological strata underlying, with MT ATES ranked highest due to the higher temperature regime currently feasible due to regulatory constraints, and LT BTES the lowest due to cost and high spatial requirements.

Storage Option:

1. MT ATES – Deep Permian and Sherwood Sandstone
2. LT ATES – Nr. Surface Aquifers – High Abstraction Potential
3. LT ATES – Nr. Surface Aquifers – Medium Abstraction Potential
4. LT BTES – i.e. everywhere where LT ATES or MT ATES is not feasible

Power Station Proximity

Using GIS it has further been possible to review the relative distance to a nearby thermal power station. The ranking has been completed using a radial distance from the centre of the district to the nearest power station. The bands used are <10km, 10-25km, 25-50km, and <100km.

10.1.2 Power Station by Power Station Review

The power station by power station analysis has been completed by considering the following:

1. Geological Storage Option
2. Heat Supply and Demand Ratio

Geological Storage has been ranked as per the district analysis but using an additional 5km buffer to include power stations which do not directly lie over a preferred geological unit but could utilise a storage unit nearby.

Heat Supply and Demand Ratio

The following synthetic graphs outline the 3 simplified variations of heat balance (supply versus demand) that are apparent when analysing each of the power stations and local heat demand.

Scenario 1 (see Figure 121*):* Demand much greater than supply throughout the year – this means there is essentially no residual heat for seasonal heat storage. Heat can be pumped directly to the local network(s) throughout the year to contribute to demand but no further seasonal heat can be used during the shoulder months and winter. There is the potential to reduce electricity efficiency in the power station to increase heat supply, this may then lead to heat storage requirement and the ability to contribute further to total heat demand.

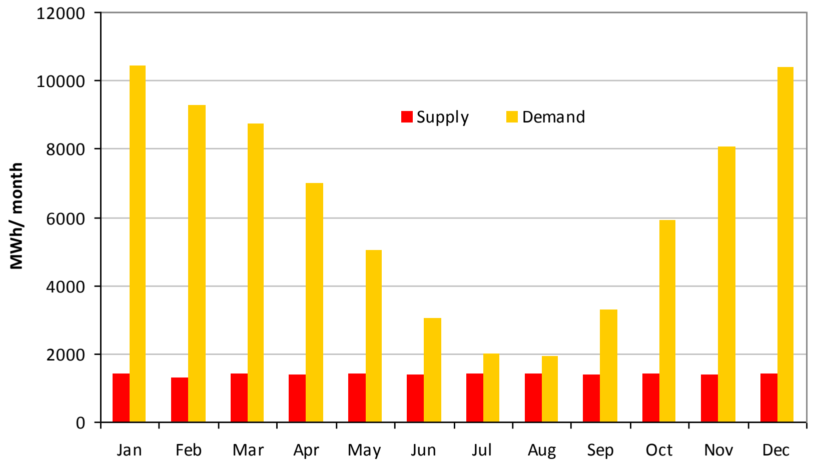

Figure 121 Scenario 1 - Demand remains higher than supply throughout the year

*Scenario 2 (*Figure 122*):* Supply much greater than demand throughout the year – direct heating I therefore possible throughout the year and storage will have no benefit. A future increase in capacity in the local area may improve the heat supply and demand balance.

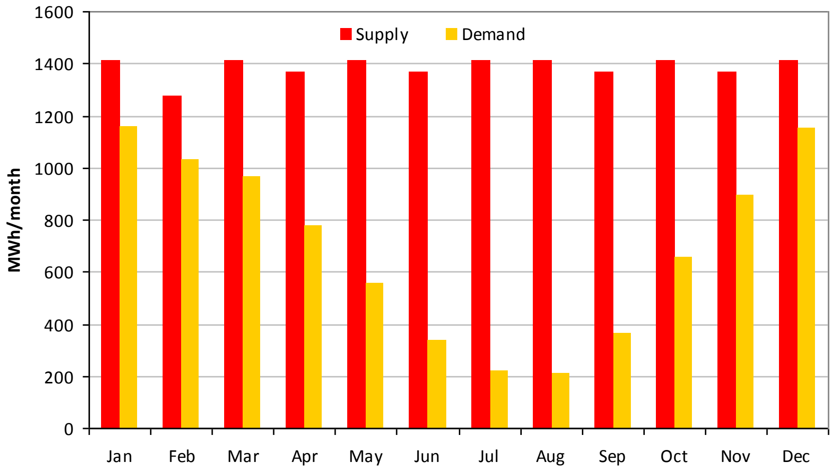

Figure 122 Supply remains higher than Demand throughout the year

*Scenario 3 (***Figure 123***):* Near annual balance between demand and supply – this results in residual heat during the summer from the power station which can be stored in the ground to cover demand in the winter.

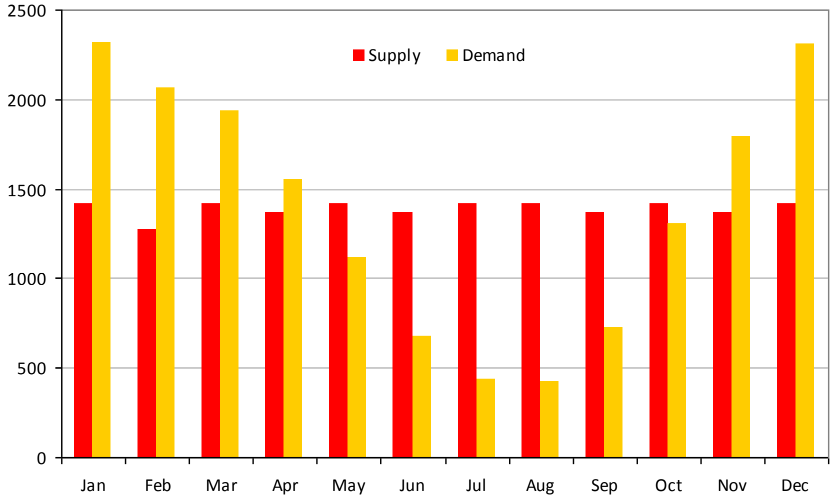

Figure 123 Significant Quantities of Excess Heat are available during the Summer

Due to the three scenarios possible and the need to ascertain where geological heat storage is beneficial a methodology was required to assess each power station with respect to agglomerated nearby demand.

The first step necessitated analysing the degree days for each region in the UK and calculating the supply and demand profiles for each power station. It was then possible to set a threshold for the annual demand/ supply ratio that results in each scenario, as follows:

Scenario 1: (Annual Demand >> Annual Supply) – Threshold set at >2.5

Example:

Power Station Thermal Output = 16,500GWh/ annum

Agglomeration Heat Demand within 100km = 80,000GWh/ annum

Demand/ Supply Ratio = 4.8

Scenario 2: (Annual Supply >> Annual Demand) – Threshold set at <0.5

Example:

Power Station Thermal Output = 16,500GWh/ annum

Agglomeration Heat Demand within 10km = 5,000GWh/ annum

Demand/ Supply Ratio = 0.3

Scenario 3: (Seasonal Storage Beneficial) – Threshold set between <2.5 and >0.5

Example:

Power Station Thermal Output = 16,500GWh/ annum

Agglomeration Heat Demand within 25km = 27,000GWh/ annum

Demand/ Supply Ratio = 1.6

Four distances were considered for each power station; 10, 25, 50 and 100km to enable the assessment to consider different scales of heat network.

10.2 Multi-Criteria Analysis Scoring

Table 46 and Table 47 indicate the scoring mechanism used for the MSOA and Power Stations, respectively.

Table 46 Multi Criteria Analysis - MSOA Scoring

Parameter	**Threshold**	**MCA Score**
Heat Density (HD)	>30kWh/m^2 (within an agglomeration)	10
(within an agglomeration)	>10kWh/m^2 and adjacent to district with HD >30kWhm^2	7
(not within an agglomeration)	>10kWh/m^2	3
Storage Option	MT ATES	3
	LT ATES	3
	LT ATES	1
	LT BTES	1
Power Station Proximity	<10km	10
	<25km	7
	>25km, <50km	3
	>50km, <100km	1
Agglomeration Size	>1,000 GWh/ annum	5
	>750 GWh/ annum	4
	>500 GWh/ annum	3
	>250 GWh/ annum	2
	100-250 GWh/ annum	1

High scores have been allocated to heat density and power station proximity with lower relative bias for storage and agglomeration size. It is envisaged that there will be a preference for mass storage at, or near to, the power station. However, local storage may prove beneficial particularly if storage at the power station is not feasible. A larger agglomeration reduces the marginal cost per kWh for the primary heat distribution so therefore, reducing the heat cost.

The total potential score is therefore 28; the following bands have been also been created to indicate relative potential for each district:

>25 – High potential (nearby power station, high heat density, suitable hydrogeology, part of large agglomeration)

20-25 – Medium potential (strong criteria in some categories but marginal cost for heat maybe higher due to, in particular, the distance to a nearby power station and low cumulative agglomeration heat load)

10-20 – Limited potential due to critical criteria such as power station locality, agglomeration heat demand

<10 – Very little or no potential due to combination of missing critical criteria

Table 47 MCA - Power Station Scoring

Parameter	**Threshold**	**Score**
Storage Option	MT ATES	10
	LT ATES (High Potential)	7
	LT ATES (Medium Potential)	3
	LT BTES	1
Demand/ Supply Ratio	Demand>>Supply	3
	Supply>> Demand	3
	Storage Beneficial	10

The maximum score possible is 20; the following bands have been used for

Score 20 = High potential for heat storage due to geology and potential supply and demand balance

Score 17 = Medium potential for heat storage due to geology and potential supply and demand balance.

Score <17 = limited potential due to geology or dominating demand and/ or supply

This MCA has been completed for a radius of 10km, 25km, 50km and 100km.

10.2.1 Multi Criteria Analysis Results

Headline Results for MSOA MCA

The headline results for the MSOA analysis are shown in Table 48 and Figure 124. Total calculated LTHW heat demand using the MSOA gas data has been calculated as 430,329GWh/ annum. This does not take into account electrical, oil and other forms of heating.

Table 48 MSOA Headline Results

Parameter	**Threshold**	**Value**	**%**
Heat Density	$>30kWh/m^2$ (within an agglomeration)	42,590GWh/ annum	10%
(within an agglomeration)	$>10kWh/m^2$ and adjacent to district with HD $>30kWhm^2$	189,770GWh/ annum	44%
(not within an agglomeration)	$>10kWh/m^2$	29,572GWH/ annum	7%
Power Station Proximity	<10km	1,235 MSOAs within 10km of a thermal power station	13%
	<25km	3,013 MSOAs within 25km	32%
	>25km, <50km	3,858 MSOAs within 50km	41%
	>50km, <100km	948 MSOAs within 100km	10%

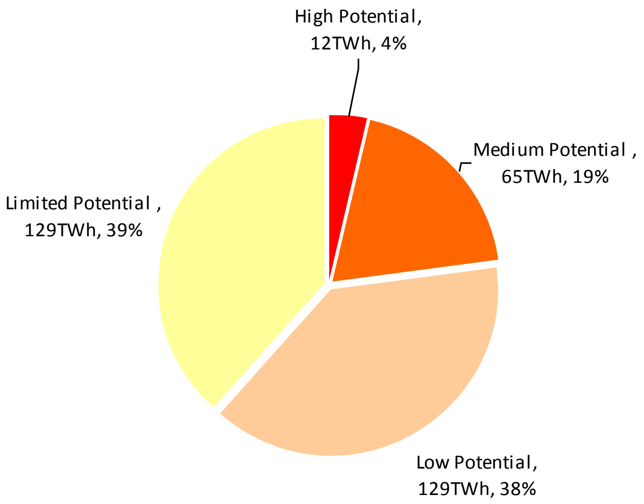

Figure 124 Multi-Criteria analysis for MSOAs

Those areas showing high and/ or medium potential equate 23% if the total MSOAs in the UK. Reference Maps for the MSOA MCA are shown in the previous chapter.

Power Station Headline results

The results for the MCA analysis are shown in Table 49, Figure 125 and Figure 126.

Table 49 MCA - Power Station Headline Results

Parameter	Threshold	Power Stations	%
Storage Option	MT ATES	15	28%
	LT ATES (High Potential)	18	34%
	LT ATES (Medium Potential)	7	13%
	LT BTES	13	25%
Demand/ Supply Ratio	Demand>>Supply	See Figure 125.	

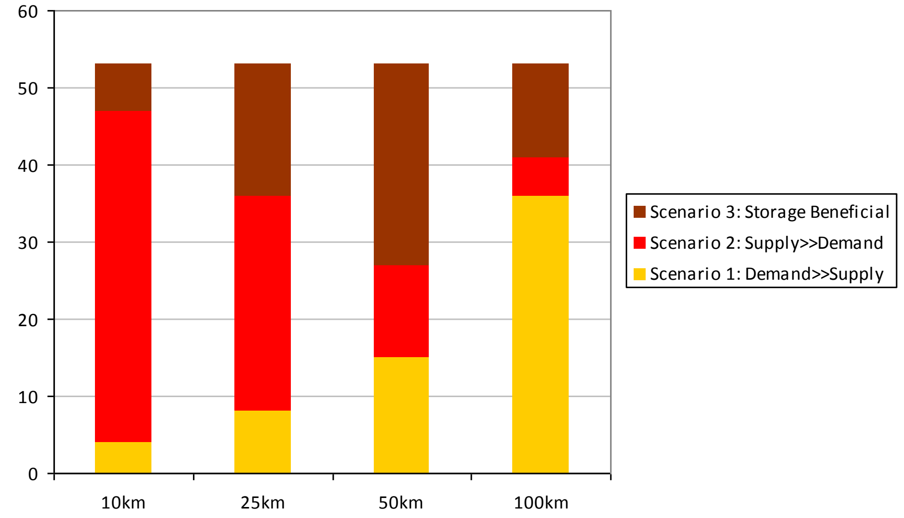

Figure 125 Demand versus Supply Ratio Results

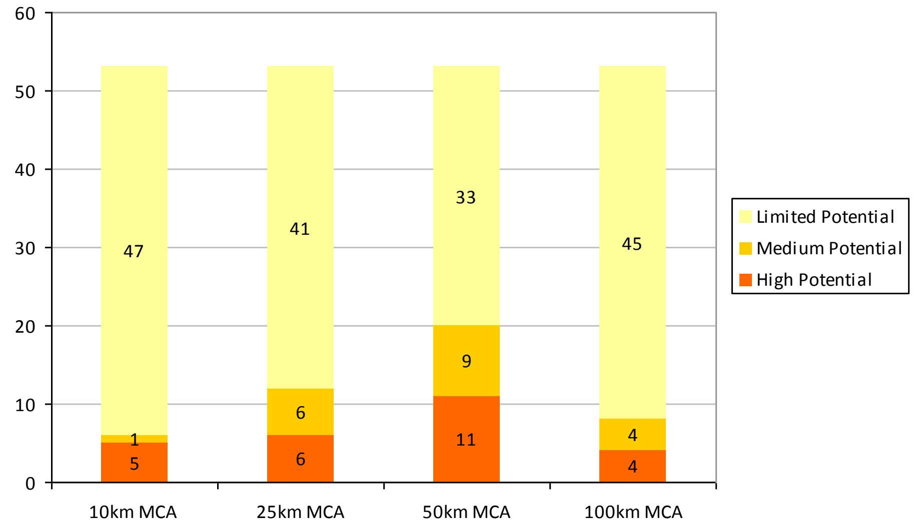

Figure 126 Interim Power Station MCA Results

The results showing varying potential dependent on the radial distance for demand assessment and the demand/ supply. At a distance of 25km, 12 power stations show high or medium potential for geological storage.

Reference GIS Maps for Power Station Analysis are shown in the previous chapter.

11 Geotechnical Analysis

11.1 Introduction

This section of the report addresses potential effects of the ground heat storage facility on the existing structures / infrastructure from a geotechnical perspective; aspects associated with the geothermal performance of the heat storage facility have been considered elsewhere in this report.

11.2 Considerations

Two general heat storage systems have been considered throughout this project:

1. Shallow storage systems where heat is pumped into an aquifer (Sandstone considered at present) at a depth of generally 0m bgl (metres below ground level) to 100m bgl. Shallow heat storage systems will experience maximum temperatures of approximately 35°C.
2. Deep storage systems where heat is pumped into an aquifer (Sandstone considered at present) at a depth of approximately 300 m bgl to 400m bgl. Deep heat storage systems will experience maximum temperatures of approximately 120°C.

Only open-loop systems have been considered for both shallow and deep heat storage systems; closed-loop systems are unlikely to have particular geotechnical implications which are not also applicable to open-loop systems.

11.2.1 Shallow Aquifers

The 35°C maximum storage temperature has been adjudged likely to cause negligible temperature-related issues (ambient temperatures in the shallow soils is considered to be approximately 11°C).

The main area of interest considered for shallow aquifers is the effect of subsistence due to water extraction and subsequent drawdown of the water table and conversely potential ground heave or adverse effects on structures due to reduced effective stresses as a result of water injection and subsequent groundwater table rises. These effects are due to changes in vertical effective stress with depth. A one-dimensional elastic assessment has been undertaken to qualify the potential issue using groundwater profile characteristics derived elsewhere in this report.

11.2.2 Deep Aquifers

As with the shallow heat storage system, relatively modest groundwater level / pressure changes will be generated in deep aquifer heat storage systems (in the order of +20m / -5m, or +200kPa / -50kPa, change in head). At depths of 300m bgl to 400m bgl, this is unlikely to have significant effects due to the intrinsic magnitude of stresses located at such depths.

The major geotechnical issues associated with deep aquifers are likely to be caused as a result of the relatively high temperatures stored (maximum temperatures of approximately 120°C). A review of available information has been carried out to determine any subsequent effects of these temperatures, with particular emphasis on Sandstone as this is the storage medium currently considered. A summary of the research reviewed is included below.

Rao et al. (2007) investigated the ‘Experimental Study of Mechanical Properties of Sandstone at High Temperature’ by undertaking laboratory testing on sandstone samples at temperatures ranging from 20°C to 300°C. The paper concludes that:

1. Uniaxial tensile strength, uniaxial compressive strength and elastic modulus increase linearly with increasing temperature below 250°C and decrease above 250°C.
2. Mode I fracture toughness increase linearly with temperature below 200°C and decrease slightly below 200°C.
3. Minerals and microstructures of natural rock material have great influences on its mechanical properties at high temperature. Whether the mechanical properties of rock are improved or degraded depends greatly on which is more dominant, drying or microcracking.

Zhou et al. (2006) investigated the ‘Experimental Study on Mechanical Property of Thermo-mechanical and Hydro-mechanical Coupling Condition for a Sandstone’, by undertaking triaxial laboratory testing on sandstone samples at confining pressures ranging from 0MPa to 60MPa, pore pressures ranging from 0MPa to 10MPa and temperatures ranging from 25°C to 70°C. The paper concludes that:

1. The strength of the sandstone increases with increasing temperature at lower confining pressures, but tends to decrease with increasing temperature at higher confining pressures.
2. The strength of the sandstone decreases with increasing pore pressure at different confining pressures.
3. The average stiffness modulus of the sandstone increases slightly with confining pressure at a temperature of 25°C. At temperatures of 50°C and 70°C, the average stiffness modulus of the rock has no clear tendency with increasing confining pressure.
4. The average stiffness modulus generally increases with increasing temperature between 25°C and 50°C. At temperatures between 50°C and 70°C, the average stiffness modulus was found to decrease with increasing temperature.

Somerton et al. (1965) investigated the ‘Thermal Alteration of Sandstones’. The research found no changes in permeability between 75°F and 350°F (between approximately 25°C and 175°C). At temperatures well above 500°F (approximately 260°C), permanent structural damage and decomposition of rock minerals was recorded as a result of thermal stresses.

Conversely, Aruna (1976) in the research report entitled 'The Effects of Temperature and Pressure on Absolute Permeability of Sandstones' recorded decreasing absolute permeability (for water in consolidated Sandstone) with increased temperature between 70°F and 300°F (approximately 20°C and 150°C) at range of confining pressures. This decrease in absolute permeability was found to be partially reversible once temperatures were again reduced.

Additionally Zhang and Hiangyi (2010) explore gas permeability in their paper 'The Experiments Study of Tight Gas Sandstone Permeability by Effective Stress and Temperature Coupling' and conclude that "temperature sensitivity leads to permeability reduction of rocks by changing their pore structure through mineral particle volume expansion indirectly… Under the joint action of high effective stress and rising temperature, seepage space in reservoirs tends to become smaller, the permeability will greatly reduce by stress and temperature coupling".

Considering the above sources, it is not currently possible to draw definite conclusions regarding the effects of temperature on the strength, stiffness and permeability of Sandstones. The results obtained are likely to be specific to the nature of the sample tested, the test method adopted and the range of temperature applied during laboratory testing.

Potential effects of Sandstone expansion due to temperature increase have been assessed using a series of finite element models.

11.3 Analyses

11.3.1 Ground Movements Resulting From a Change in Groundwater Conditions

Analyses have been undertaken in order to quantify the potential for ground movement due to groundwater drawdown / rise in the vicinity of the inlet / output well. A characteristic one-dimensional analysis has been undertaken using a generalised ground profile and a groundwater profile determined from geothermal operations models presented elsewhere in this report.

An elastic model has been adopted, with settlements (ρ) calculated for a series of strips (with depth) according to the following expression:

$$\rho = m_v \sigma_z H$$

Where: m_v = the coefficient of volume compressibility obtained for the effective pressure increment in the particular layer under consideration (note: m_v is the inverse of the drained stiffness).

σ_z = the change in effective vertical stress imposed on a particular soil layer as a result of change in groundwater level.

H = the thickness of the particular soil layer under consideration.

The settlement calculated for each strip is summed with depth in order to calculate a total one-dimensional settlement at a given location.

In order to assess the effects of changing groundwater levels in a shallow heat storage aquifer, a conservative drained stiffness profile of E' = 20 + 1z MPa (where z is the depth below ground level) has been assumed with rock (effectively a rigid boundary) at 100m bgl. The groundwater level changes (shown in Figure 127) have been adopted for this analysis with an assumed original groundwater table at 20m bgl.

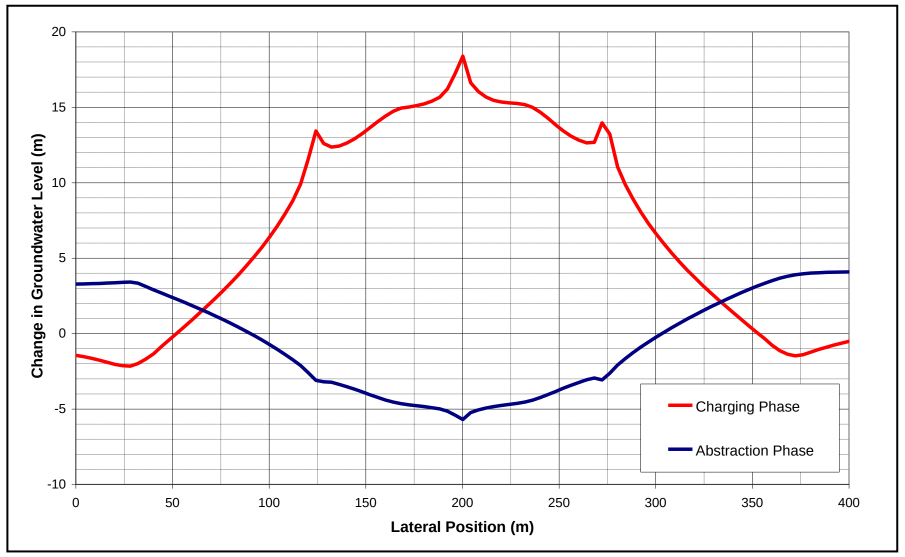

Figure 127 Change in groundwater level during changing and abstraction phases

The maximum increase in groundwater level (18.4m; therefore groundwater level at 1.6m bgl) has been calculated to produce a heave of approximately 250mm. The maximum decrease in groundwater level (5.7m; therefore groundwater level at 25.7m bgl) has been calculated to produce a settlement of approximately 60mm. The greatest groundwater level gradient for either the charging or abstraction phases is a change in groundwater level of approximately 2.2m over a lateral distance of 4m; this will produce differential settlements at ground level in the order of 1-in-125 (1v: 125h), which would have significant potential to affect structures.

Potential ground movement effects resulting from a change in groundwater pressure in a deep Sandstone aquifer have also been assessed using the aforementioned one-dimensional consolidation method. In addition to the soil stiffness profile assumed above, a constant stiffness of 50MPa and 100MPa was assumed for the Mudstone and Sandstone strata respectively as shown in the following table:

Stratum	Depth (m bgl)	Soil / Rock Stiffness (MPa)	Soil / Rock Stiffness Gradient (MPa/m)
General Soil	0 to 100	20	1
Mudstone	100 to 300	50	0
Sandstone	300 to 400	100	0

* Groundwater table placed at ground level.

** Rigid boundary placed below Sandstone aquifer.

For the purpose of this indicative calculation, the increase in groundwater head shown in Figure 127 above was applied throughout the full depth of the Sandstone aquifer as an addition to the original hydrostatic groundwater head in this stratum.

The greatest increase in groundwater head of 18.4m when applied in the Sandstone aquifer has been calculated to produce a heave of approximately 18mm. The maximum decrease in groundwater head of 5.7m when applied in the Sandstone aquifer has been calculated to produce a settlement of approximately 6mm. The greatest groundwater level gradient for either the charging or abstraction phases has been calculated to produce differential settlements at ground level in the order of 1-in-1800 (1v: 1800), which is unlikely to have significant potential to affect the majority of structures.

11.3.2 Ground Movements Resulting From Temperature Expansion of Aquifer

Analyses have been undertaken to assess potential near-surface ground movements due to thermal expansion of the Sandstone stratum. A two-dimensional, axisymmetric finite element model has been adopted to assess expansion effects for the deep heat storage aquifer scenario which will experience the greatest potential change in temperature (maximum temperatures of approximately 120°C). The models use imposed displacements to assess ground movements, in the form of both vertical displacements at the upper interface of the sandstone and volumetric expansion of the Sandstone.

A literature review undertaken indicates that published values for the thermal expansion coefficient of sandstone range from approximately 10.0×10^{-6} /°C to 12.5×10^{-6} /°C; the latter (more conservative) value has been adopted in this analysis for the full Sandstone mass. In the Sandia Laboratories Energy Report entitled ‘Pressure Effects on Thermal Conductivity and Expansion of Geological Materials’, James Sweet notes that “for most types of rock… the predicted effect of a 100MPa pressure on thermal expansion is to cause a decrease of 10% or less in this quantity. For porus rock, such as sandstone, the effect will be larger, with a 25% reduction”.

At depths of up to 400m, as considered in this analysis, in-situ total vertical stresses of up to 10MPa are anticipated; subsequently, the thermal expansion value adopted in this analysis ($a = 12.5 \times 10^{-6}$ /°C) is likely to be conservative in this respect.

The following ground model has been adopted for these analyses:

Stratum	Depth (m bgl)	Soil / Rock Stiffness (MPa)	Soil / Rock Stiffness Gradient (MPa/m)
General Soil	0 to 100	20	1
Mudstone	100 to 300	50	0
Sandstone	300 to 400	100	0

* Groundwater table placed at ground level.

** $K_0 = 1$ throughout all strata.

The following thermal profile has been adopted throughout the Sandstone stratum. The ambient temperature in the sandstone has been assumed to be 20°C.

Lateral Distance from Centre of Axisymmetric Model (m)	Temperature (°C)	Temperature Increase (°C)
0	120	100
85	120	100
160	55	35
210	20	0

* Temperature constant vertically throughout sandstone.

** Lateral temperature gradient currently assumed linear between above points.

The set of first models assessed apply an upward vertical displacement at the interface of the sandstone and overlying mudstone in order to simulate expansion of the sandstone aquifer. The magnitude of this displacement has currently been determined from the aforementioned coefficient of expansion, the depth of sandstone (100m) and the change in temperature at that lateral position. A screenshot of the model input is shown in Figure 128 below.

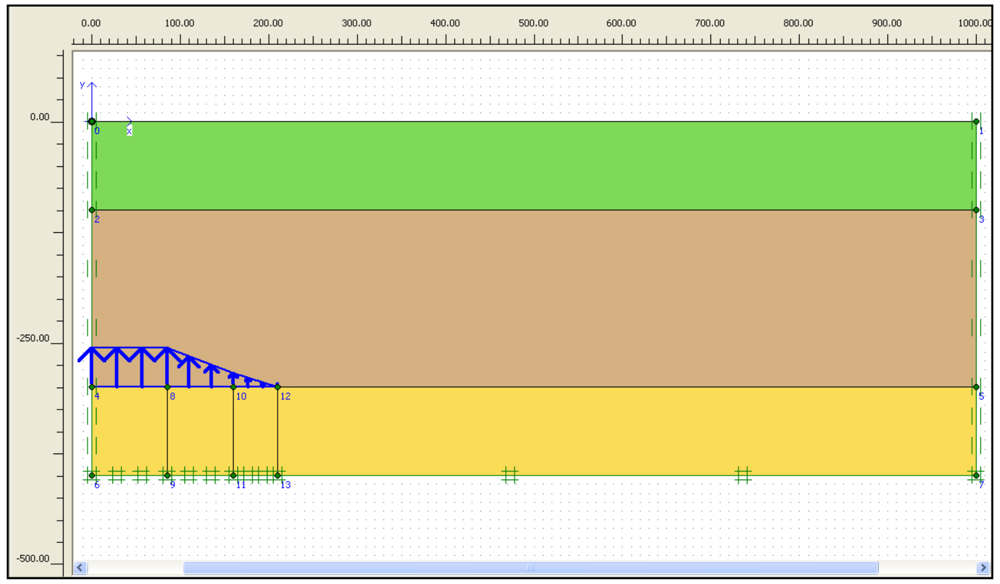

Figure 128 Input into vertical displacement 2D finite element model

The second set of models adopt the application of a volumetric expansion to the sandstone clusters which experience a change in temperature. For the purposes of this analysis, the volume of the plume has been divided into six clusters with a volumetric strain applied to each according to the average change in temperature and using the following expression:

Volumetric strain, $e_{vol} = e_x + e_y + e_z$

Assuming the sandstone is isotropic from a thermo-mechanical perspective $\alpha_x = \alpha_y = \alpha_z$,

Volumetric coefficient of thermal expansion, $\alpha_{vol} = 3\,\alpha_{linear}$

The resulting soil displacements from the volumetric strain model are shown in Figure 129 below:

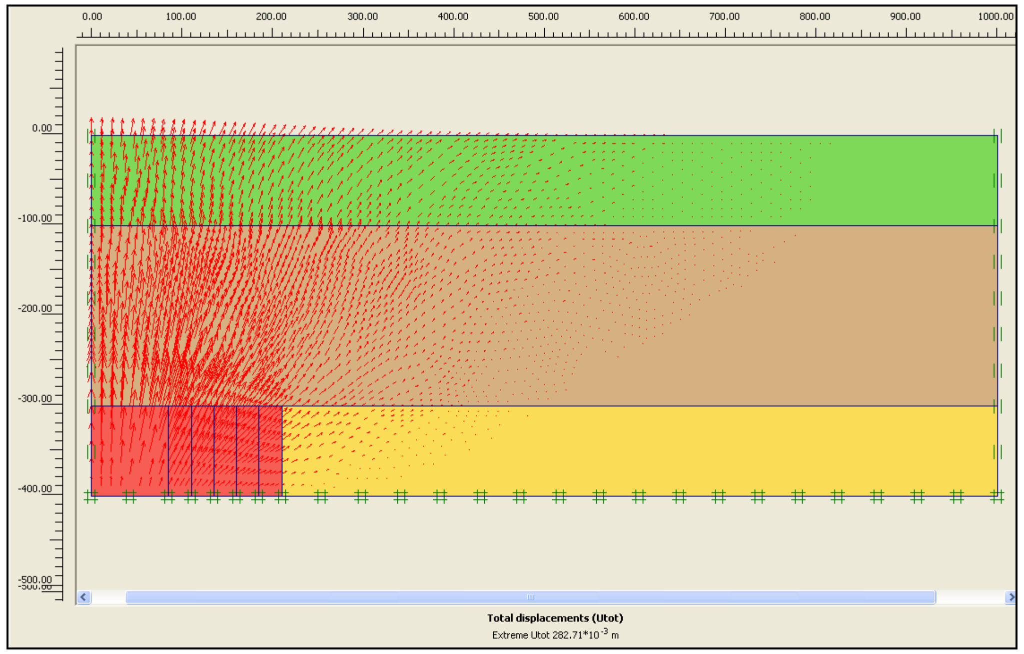

Figure 129 Displacement output from volumetric strain 2D finite element model

The effects of altering both the soil / rock stiffnesses (by a factor of magnitude), soil / rock weights and the lateral earth pressure coefficient (K_0) has been fully assessed for the both the vertical displacement and volumetric strain models and were found to have negligible effect on near-surface ground movements.

The Magnitude of vertical heave evaluated at ground level from both the vertical displacement and volumetric strain models are presented in Figure 130 below:

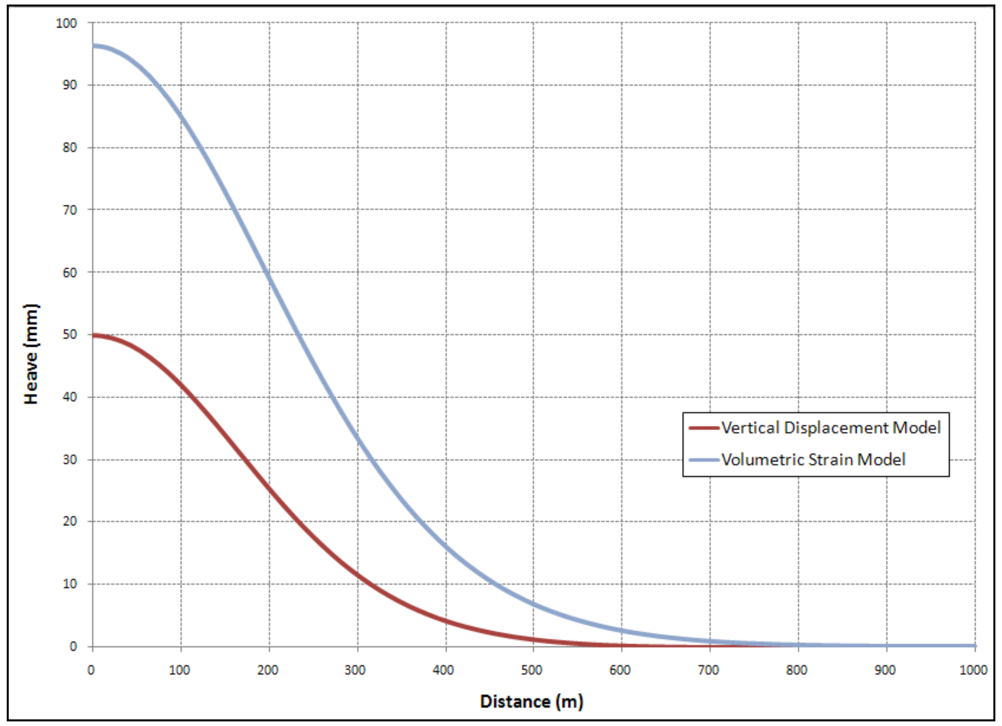

Figure 130 Comparison of typical heave magnitudes from vertical displacement and volumetric strain models

As shown in Figure 130 above, the linear-elastic models predict total heave displacements in the order of 50mm to 100mm with maximum ground movements in the centre of the axisymmetric model. The magnitude of maximum differential heave has been calculated at approximately 1-in-5500 (1v: 5500h) and 1-in-3500 (1v: 3500h) for the vertical displacement and volumetric strain models respectively. Maximum lateral ground surface movements have been calculated at 20mm and 40mm for the vertical displacement and volumetric strain models respectively.

It is the differential ground movements as opposed to total ground movements which are important in determining potential damage to near-surface structures. To demonstrate this, a parallel can be drawn with ground movements caused as a result of groundwater extraction in many major cities. In London, extraction from the Chalk (which constitutes the major aquifer under the city) over the last 200 years has lowered groundwater levels in the aquifer, generally by several tens of metres (see CIRIA SP69, 'The Engineering Implications of Rising Groundwater Levels in the Deep Aquifer Beneath London', 1989). This fall in groundwater level has resulted in much of London settling in the order of several hundred millimetres. Since the 1960s, due to a reduced rate of groundwater pumping from the Chalk, groundwater levels have steadily risen in many areas by around 1 metre per year and subsequently ground levels are now rising, returning towards their original elevation. For many buildings negligible damage has been caused as a result of such movements, as the whole soil mass is moving together and differential movements are relatively minor.

Subsequently, the magnitude of differential near-surface ground movements due to thermal expansion calculated in these analyses is unlikely to pose significant risk to structures in the vicinity of the heat-storage aquifer as the differential ground movements over the footprint of surface buildings is small.

11.4 Findings and Recommendations

A summary of the main finding and recommendations are listed as follows:

1. A literature review has been undertaken to assess thermal effects on soils and rocks with a particular emphasis on sandstone. The published literature appears to suggest conflicting findings on the key parameters of strength, stiffness and permeability.
2. Characteristic one-dimensional analyses have been undertaken to determine the potential for changes in groundwater level to cause ground settlement and heave. Using the current groundwater profiles for the abstraction and injection and a preliminary drained stiffness profile, differential settlement / heave at the ground surface has been highlighted as a possible issue for structures if the storage aquifer is shallow and of relatively low stiffness. In deeper aquifers of more competent stiffness (such as Sandstone at depths of 300m to 400m), the magnitude of differential ground movements calculated are unlikely to lead to issues for near-surface structures.
3. Finite element calculations have been undertaken in order to quantify possible effects of thermal expansion in a deep heat storage aquifer. Calculations suggest that thermal expansion of the sandstone has the potential to cause settlement / heave at ground level; however the magnitude of the differential vertical movements are not likely to cause an issue for structures at ground level.
4. A detailed site investigation will be required at an early stage for a potential heat-storage site. It is recommended that laboratory testing should include specialist analysis of rock samples from the storage aquifer to obtain site-specific information on strength, stiffness, permeability and the coefficient of thermal expansion in order to confirm the viability of the project.
5. Depending on the site constraints and in particular the sensitivity to ground movement of buildings in the vicinity of the heat storage site to, a programme of monitoring may be required during the early operational phase of the project. This may include targets on buildings and ground monitoring points.

12 Environmental Impact

12.1 Overview of EIA Process

Environmental Impact Assessment (EIA) identifies all potential environmental impacts that are likely to result from a proposed development. This information is presented in an Environmental Impact Statement (EIS). The main purpose of an EIS is to allow the decision makers, statutory consultees and all interested parties including members of the public to understand the implications of the development proposal on the environment. The EIS sets out the findings of the EIA process describing the development proposal and the information required to assess the impact of the development proposal on the environment. It includes a series of technical chapters examining in detail the potential impact of the development proposal on specific aspects of the environment. Where appropriate, the EIS describes how the design has been amended or what mitigation measures are recommended to address potential adverse environmental impacts of the proposed development. Residual impacts are also identified in the EIS. Residual impacts are those impacts that remain assuming mitigation measures have been implemented.

The requirements for Environmental Impact Assessment (EIA) and the circumstances in which one should be undertaken are established by the European Directive on ‘the assessment of the effects of certain public and private projects on the environment’ Directive 85/337/EEC (as amended by the Directive 97/11/EEC and 2003/35/EC). The European Directive has been transposed into U.K. legislation by the Town and Country Planning (Environmental Impact Assessment) (England and Wales) Regulations 1999 (EIA Regulations).

These Regulations contain two lists of development projects. Schedule 1 identifies all the types of developments for which and Environmental Impact Assessment (EIA) is mandatory irrespective of their location. Schedule 2 identifies the types of developments where an EIA must be carried out if the development if any part of the development is to be carried out in a ‘sensitive area’. The EIA Regulations define ‘sensitive areas’ as including nature conservation sites with national or higher level designations (e.g. Sites of Special Scientific Interest, Special Protection Areas, Special Areas of Conservation and Ramsar sites), Areas of Outstanding Natural Beauty, National Parks, World Heritage Sites and Scheduled Ancient Monuments.

Schedule 2 developments must also be assessed based on the likelihood to have a significant impact on the environment by virtue of its nature, size or location. Regulation 4(5) advises that, where a decision as to whether Schedule 2 development is an EIA development, account should be taken of the selection criteria as set out in Schedule 3 of the EIA Regulations. These criteria relate to the characteristics of the development, the location of the development and the characteristics of the potential impact as listed below.

The characteristics are identified as:

a) The size of the development;
b) The culmination with other development;
c) The use of natural resources;
d) The production of waste;
e) Pollution and nuisances; and
f) The risk of accidents, having regard to substances or technologies used

The location of development

Schedule 3 states that the environmental sensitivity of areas likely to be affected must be considered with regard to:

a) The existing land use;
b) The relative abundance, quality and regenerative capacity of natural resources in the area; and
c) The absorption capacity of the natural environment.

Characteristics of the potential impact

The potential significant effects of development must be considered in relation to criteria set out above, and must have regard to:

a) The extent of the impact (geographical area and size of the affected population);
b) The transfrontier nature of the impact;
c) The magnitude and complexity of the impact;
d) The probability of the impact; and
e) The duration, frequency and reversibility of the impact.

12.2 Initial EIA Considerations for the Heat Storage Installation

The proposed Geological Heat Storage development is currently not identified in the Regulations as falling within Schedule 1 or Schedule 2. If the development were to be identified under Schedule 1, an EIA would be required to be prepared. It is likely that the Geological Heat Storage projects would be considered to fall within Schedule 2 and therefore proposals would require an EIA.

During the desktop stage it will be necessary to seek a “screening opinion” from the local authority. This will require a brief letter of request as to whether the proposed development will require an EIA. It will include a basic description of the scheme and of the existing site, a comment about the screening criteria and a preliminary listing of possible effects on the environment.

Once the local planning authority confirm in their screening opinion that an EIA is required, the initial phase of work is scoping. Scoping is an important part of the EIA process and is used to ensure that all the environmental issues that could involve significant impacts are identified and appropriate methods for information collection and impact assessment are devised.

The scoping process proposed involves the following key stages:

1. Preliminary appraisal of the predicted likely effects of the proposals
2. Preliminary investigations to support effect predictions, for example desk study and site visit
3. Submission of an informal scoping report to the local planning authority
4. Confirmation from the local planning authority on the list and content of each assessment.

12.3 Methodology

The first stage in any EIA is to determine the scope of the assessment and the identification of the issues of relevance to the site and development. The scope comprises a number of elements;

1. technical,
2. spatial and
3. temporal.

Typically the technical scope requires that the Environmental Statement contains a description of the aspects of the environment likely to be significantly affected by the proposed development, including, human beings, fauna and flora, soil, water, air, climatic factors, and the landscape; material assets, including the architectural and archaeological heritage, the cultural heritage and the inter-relationship between these factors.

The spatial scope of each discipline specific assessment is determined by the scale of the works, the nature of the baseline and likely impacts. The geographical extent of the assessment varies for each of the discipline specific areas, and includes the following:

1. The site (for issues such as ground conditions)
2. Properties and land uses in the immediate vicinity (for issues such as noise, air, traffic and ecology)
3. The wider Dublin area and its surrounds (for issues such as socio-economic, visual amenity and transport).

The temporal scope is concerned to address predicted impacts or changes to the baseline over the period of the construction and operational activities and. For example, if the proposed development was expected to be completed over approximately ten years; an assessment of the impacts of the development will need to take into account the baseline situation approximately ten years hence, when the site would be fully operational.

The issues of relevance are then addressed by the following carried out in sequence;

1. baseline assessment;
2. identification of impacts;
3. assessment of significance;
4. identification of mitigation measures; determination of residual impacts;
5. outline of alternatives.

The Regulations require that a non-technical summary is produced which draws out the key issues as identified throughout the EIA process. A specific requirement of the non-technical summary is that it can be read with ease by a non-technical person and the key issues and their treatment are clear and explained in non-technical language. The non-technical summary for Connolly Station will satisfy this requirement.

Consultation is a key part of an EIA and occurs throughout the process, for example:

1. Contact with relevant organisations or bodies as part of scoping desk study, to inform and agree the scope of the EIA
2. Consultation at scoping stage and throughout the process with the relevant local planning authority
3. Ongoing consultation with relevant organisation and bodies such as the Environmental Agency (EA), English Heritage etc to inform impact assessment, and adapt the scope or scheme if necessary
4. Consultation with statutory and non-statutory bodies as part of the planning process.

12.4 Preliminary Discussion of Environmental Impacts of Geological Heat Storage

The potential impacts on the environment which could result from the construction and operation geological heat storage developments are presented below. This preliminary list is generic and will be modified to suit site specific circumstances. A brief description is given under each heading of the context, potential impacts and example mitigation. Site selection should be carefully considered for this development to reduce the potential effects to the environment. To a considerable extent, construction impacts can be mitigation through good construction management practices.

12.4.1 Construction Impacts

1. **Noise**

   Short term noise impacts from construction of the wells and related infrastructure. Background levels of noise are important and are likely to be highly variable with high ambient noise in the vicinity of the power station and possibly the user site(s), but the delivery infrastructure is linear, relatively long and may be crossing otherwise tranquil areas. Noise is likely to be generated by construction and traffic. The construction period is likely to be a period of at least one year (not months) so the effect may be relatively prolonged. Construction noise can be mitigated by appropriate choices of plant and construction technique, by acoustic barriers and restriction s on hours of working.
2. **Air quality**

   Short term air quality impacts are likely to arise mainly from dust arising from construction. Background air quality may be variable, with poorer quality possible near to power stations or urban centres whereas the delivery infrastructure may traverse areas of high air quality. Construction traffic may decrease local air quality and dust may also cause a nuisance to local residents and workers. Mitigation will be through good site management, dust suppression and vehicle routing away from sensitive areas.
3. **Traffic**

   Construction traffic could have impacts on local residences if routed down residential streets. Local traffic is likely to be disrupted by construction traffic. Mitigation will be by vehicle routing away from sensitive/ residential areas.
4. **Ground stability**

   There is a potential for ground instability to result from drilling activities. Any such impacts are likely to be localised, but could be significant if occurrence was in the vicinity of existing sensitive buildings or infrastructure. Mitigation will be though appropriate investigation, assessment and design. If potential impacts were identified, monitoring of ground movement may be necessary.
5. **Visual amenity**

   Impacts to visual amenity during construction are primarily restricted to drilling rigs at the well site. If the well site is in the vicinity of the power station any such impact likely to be limited. Any impact is unlikely to be prolonged.
6. **Heritage**

   Impacts to existing heritage issues, for example heritage buildings or landscapes will be very site specific. Any features of archaeological or cultural heritage interest need to be identified and recorded prior to construction to allow appropriate (and agreed) mitigation. Above ground features could all be recorded prior to construction activities occurring, however excavation for the infrastructure and drilling may require archaeological monitoring in the shallow soils.
7. **Water quality**

   There is potential for impact on any local surface water courses (e.g. from sediment runoff, or uncontrolled discharge of dewatering activities in excavations etc. Any such impacts are highly dependent on the proximity of the site to a water course, the sensitivity of the receiving water and the general topography of the site. Mitigation will be through good site management, control of run-off by barriers/ temporary drains and routing construction away from sensitive areas.
8. **Ecology**

   Impacts to aquatic or terrestrial ecology will be very site specific. The EIA process will be used to understand the likely ecological impacts of the proposals and suggest methods for reducing or removing these, as well as describing ecological enhancement appropriate to the site. Ecological enhancement could include the introduction of locally appropriate habitats to the site and/or planting with native species.
9. **Hydrology and hydrogeology**

   A flood risk assessment will be carried out, which will determine any site specific potential flooding and the effect of the proposed development on flooding elsewhere. Earthworks could mobilise any near surface contaminants into groundwater. Mitigation will be site specific and will be informed by detailed site investigations.
10. **Waste**

    Potentially large volumes of waste will be generated as a result of the construction of boreholes and excavation for the infrastructure. Some near surface spoil is likely to be contaminated, which will require treatment prior to re-use or disposal. The development will also generate waste products during the construction phase in the form of off-cuts of building materials, materials packaging and workers' food and packaging waste. The potential impacts relating to waste will be assessed as part of the EIA. It is likely that many impacts can be reduced through careful planning of waste infrastructure and systems in the form of a site waste management plan (SWMP) to reduce the impacts of construction waste.

12.4.2 Operational Impacts

1. **Noise**

   Source noise levels will be derived for all noise sources associated with the proposed development during the operational phase. The likely level of noise emissions from the development will be predicted in accordance with standard guidance. Where appropriate distance attenuation, barrier screening, ground topography and meteorological conditions will be taken into account. Operational equipment and plant will be appropriately housed, minimising noise generation. Operational noise impacts off-site associated with the running of the above ground infrastructure is likely to be very limited.

2. **Air quality**

   Operational impacts on air quality are likely to limited to those associated with traffic (see below) etc.

3. **Traffic**

   Anticipated to be a relatively small increase in traffic due to operation of the development (e.g. operational and maintenance staff) at the well site which could have impacts on local residences if routed down residential streets. Mitigation, if needed, will be by vehicle routing away from sensitive/ residential areas.

4. **Ground stability**

   There is a limited potential that ground movements could result during the operation of the system as a result of the repeated cycles of heat abstraction and recharge. This potential risk will be subject to detailed investigation, modelling, assessment, and agreement with the local authority and as appropriate, could be subject to long term monitoring.

5. **Visual amenity**

   Impacts to visual amenity in operation are primarily restricted to buildings housing pumps and heat exchangers etc) at the well site. If the well site is in the vicinity of the power station any such impact likely to be limited.

6. **Water quality and hydrogeology**

   The principle potential impact on water quality during operation is related to the use of groundwater to extract and recharge heat. The sensitivity of the site will reflect the type of the aquifer, proximity to abstractions and the connectivity with other water resources such as rivers, wetlands and associated ecology. The potential impacts will also reflect the temperature of the recharge water, the use of any chemicals, the depth of recharge and extraction etc. The potential risks will be subject to detailed modelling, assessment, liaison and agreement with the Environment Agency and will be subject to long term monitoring.

7. **Ecology**

   Operational impacts associated with the above ground plant and distribution infrastructure to aquatic or terrestrial ecology are unlikely to be significant. Potentially more important impacts related to aquatic ecology are identified above and the discussion on construction impacts on ecology above is also relevant during the operational phase.

8. **Waste**

   Waste generated by the offices and operations buildings will not represent a significant increase in waste generated by the site, over existing conditions. Impacts from operation are expected to include a marginal increase in pressure on local waste management infrastructure capacity. Transporting this waste has limited impacts associated with increased traffic, noise and a reduction in local air quality, and the combustion of fossil fuels.

13 Regulatory Review

13.1 Planning legislation and regulation

The land use planning system helps to ensure that development takes place in the public interest, in economically, socially and environmentally sustainable ways. Each country of the United Kingdom has its own planning system that is responsible for town and country planning devolved to the Northern Ireland Assembly, the Scottish Parliament and the Welsh Assembly. Current planning legislation for England and Wales is consolidated in the Town and Country Planning Act 1990.

Planning permission is required for any development of land or property unless the development is specifically exempted from this need. Development includes the carrying out of works (e.g. building on land), which makes a material (i.e. significant) change of the use of the land. Categories of exempted development are set out in planning law and these are usually related to certain thresholds (e.g. size or height). Where the thresholds are exceeded exemptions will no longer apply.

It appears that the development of the nature and scale envisaged in the underground heat storage project and the associated infrastructure would require planning permission.

The development policies and objectives of each local planning authority are set out in its local development plan. Planning applications would normally be required to generally meet these local policies and objectives. In their applications it is the responsibility of the developers to demonstrate that they have addressed all matters of material planning consideration. These matters are listed in the legislation and include a wide variety of matters including for example, sustainability, renewable energy, flood risk etc. All of these issues currently benefit from detailed guidance presented in a series of Planning Policy Guidance notes (PPGs) or Planning Policy Statements (PPSs). The government is currently in the early stages of consulting on its proposals to simplify the planning system which includes the introduction of a National Planning Policy Framework (NPPF) and removal of much of this detailed guidance.

Planning permission is normally subject to certain Conditions, which are listed on the local planning authority's decision notice. These Conditions may require changes/ amendments to the developer's proposals and contributions to the local authority for particular services (e.g. the road network etc). These contributions differ from place to place and for different types of development.

As per the consideration of an EIA, this type is unprecedented and early consultation will be needed with the local planning authority to review concerns that are specific to each installation and the immediate, local and regional context.

13.2 Consents and the Environment Agency

According to the Environment Agency, and in England and Wales, closed loop systems do not currently require any formal comment or licence from the Environment Agency. However, the Environment Agency would normally be consulted as a part of any application for planning permission where Controlled Waters were potentially affected or involved (as in this case). As indicated by the early consultations earlier in this project, the Environment Agency would be concerned to ensure that any geological heat storage system did not give rise to any unacceptable levels of risk to aquifers. An assessment of the potential risks and identification of possible mitigation measures would be required for review by the Environment Agency (and would include assessment of the potential risks to any nearby abstractions, use of chemicals in the system etc).

The authorisation process for any open loop geological heat storage systems is likely to broadly follow the current staged process for open loop ground source heat pump systems. This is currently set out in the Environment Agency "Environmental good practice guide for ground source heating and cooling" (Ref GEHO0311BTPA-E-E). However, the Environment Agency has indicated that it is likely a detailed assessment of all potential environmental risks that could be realised by any specific proposals and this level of assessment (and the associated level of scrutiny by the Environment Agency) would increase with the site-specific particulars of the system being proposed (particularly temperature).

It is anticipated that the process would follow the steps shown in Table 50.

Table 50 Regulatory Process for Heat Storage Projects

Step	Description	Objective
Step 1	Initiate contact and preliminary discussions with the Environment Agency	To inform the Environment Agency of the proposal To obtain initial Environment Agency views To identify any particular areas of risk
Step 2	Application for consent to investigate a groundwater source	In accordance with requirements of Section 32 of the Water Resources Act 1991. This would enable the completion of pumping and injection tests to establish the sustainability of yield and injection characteristics.
Step 3 *[Potential]*	Carry out a water features survey	May be required in locations of hydrological and/ or hydrogeological sensitivity Nature and extent of the survey will be site specific.
Step 4(a)	Pumping (abstraction) tests	To determine volume and sustainability of yield. Provide data of aquifer parameters [for risk assessment and re-injection]
Step 4(b)	Pumping (re-charge) test [Requires application for a temporary environmental permit]	To determine hydraulic response of the aquifer Note: Re-charged water must be re-injected into the aquifer from which it was abstracted.
Step 5	Application for Abstraction Licence and for Discharge Consent [Environmental Permit].	Application must demonstrate; - a detailed understanding of the performance of the aquifer - justification of the need for proposed volumes, temperatures etc. The Application will also need to address environmental, social and economic aspects in a sustainability appraisal.
Step 6	Compliance with Environment Agency Licence Conditions	Conditions will state inter alia volumes, temperatures of both abstraction and re-injection Monitoring will be required to demonstrate compliance with these Conditions.

Table 51 is repeated from the IWP 2 and indicates the Environment Agency current response to the system design consideration. Any further consultation will require a detailed proposal for a specific site, i.e. an initial pilot study.

Table 51 IWP 2 Updated Regulatory Review

Strata utilised (depths)	Open loop		Closed loop	
	Shallow aquifers	**Deep aquifers**	**Shallow non-aquifer strata**	**Deep non-aquifer strata**
Temperature	**(near surface to 200m)**	**(200 – 800m)**	**(up to ~200m or deeper)**	**(up to ~200m or deeper)**
35°C	Theoretically possible (subject to the risk assessment)		Not currently regulated; however, modelling works will inevitably lead to an understanding on expectedly low effects on 'heat reservoir' surroundings.	Not currently regulated; however, modelling works will inevitably lead to an understanding on expectedly low effects on 'heat reservoir' surroundings)
EA Response	*The EA would request detailed work on how the proposed activity would affect the environment, i.e. the water resource, temperature of other abstractions, receptors such as wetlands, lakes, rivers and associated ecology, impacts on pollutant movement etc. There is not one scheme that the EA regulate with discharge temperatures over 35C.*		*There are environmental risks with this activity with regards to the type of aquifer (the scheme interconnecting different aquifer units etc), proximity to abstractions (e.g. in SPZ1) and the use of certain chemicals circulating in the closed loop system. Further details are in the Environment Agency's environmental good practice guide for ground source heating and cooling. The EA do not currently regulate these schemes but there is an expectation responsible designers, installers and operators will undertake a risk assessment of the environmental risks and mitigate them so as to prevent pollution and any resulting liabilities for impacts on third party assets.* *The EA have the power to serve a notice to stop an activity or require an activity to have an environmental permit if they believe the proposal to have an unacceptable risk of pollution. The EA define almost all lithologies as aquifers, even very low yielding bedrock. The EA have a remit to protect all abstractions (including small private water supplies), designated wetlands etc. which may be on very low productivity aquifers.*	
120°C	Unlikely to be feasible due to adverse effects caused by changes in physical and chemical properties.	Theoretically possible (subject to the risk assessment demonstrating sufficient separation to nearby/overlaying freshwater aquifers).	Although not currently regulated, environmental impacts to the freshwater aquifer is deemed prohibitive	Subject to the risk assessment demonstrating 'no unacceptable' effect to nearby freshwater aquifer systems or ground integrity of non-aquifer unit. Will be difficult to install however.
EA Response	*The EA will require a detailed environmental risk assessment to be completed as this temperature water could significantly impact other abstractions, which may also be deep.*		*The EA have a remit to protect all abstractions (including small private water supplies), designated wetlands etc. which may be on very low productivity aquifers.*	

14 Intellectual Property Review

A high level review of the potential for intellectual property has been carried out. Due to the nature of this study it is not been possible to conduct a more detailed patent search or due diligence. Further to our initial suggestions in the contract we believe this is better placed during the project pilot study and detailed design phases where closer inspection of the systems and technologies may allow identification of more novel and innovative approaches.

However, for the benefit of the report we have split the system down (see Figure 131) to enable some suggestions to be made which can be further investigated at a later date. Essentially the system configuration considered uses existing technologies and approaches which are relatively well established. Due to the scale of the system there maybe opportunities to speed installations and reduce costs through innovation. IP potential for each aspect of the system has been initially considered in Table 52, This will be expanded upon during final report writing where certain ideas are developed.

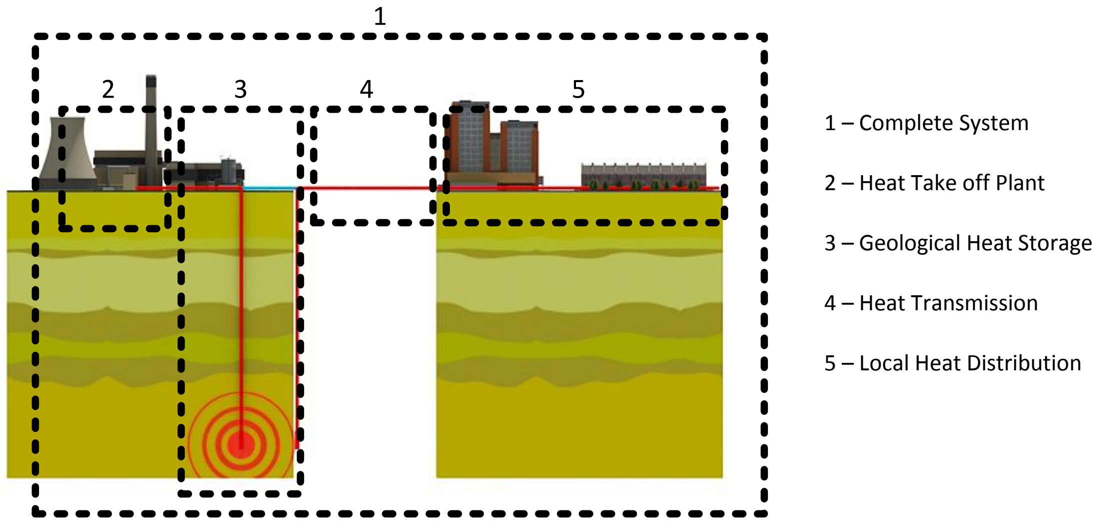

Figure 131 Simple Breakdown of Power Station, Storage and Distribution Network

Table 52 High Level Intellectual Potential Review

System Area	IP Potential
1	Overall System- Limited potential for IP exists as the system combines existing approaches and techniques Unprecedented deployment of heat distribution could benefit from an innovative procurement strategy to link together private companies and public bodies.
2	Heat Take Off from Turbine Plant Retro-fitting of Existing plant to enable heat take off at higher temperature may require innovation, particularly to allow flexibility between heat take off and maximising electrical efficiency.
3	Geological Storage Materials for high temperature well casing. Currently, PVC is not suitable at depth and for high temperature. Stainless steel costing may drive the need to consider alternative plastic composites that overcome this issue. Fast installation methods for drilling and well casing to great depth Enhancement of storage volume, potentially using Enhanced Geothermal System (EGS) approaches. Currently, EGS is being deployed to enable the flow of groundwater through higher temperature geological sequences with minimal impact on storage capacity. Possible hybrid of geological heat storage and EGS would enable the use of waste heat to raise the temperature of the naturally occurring resource during the summer, and/or using industrial waste heat. The application of EGS in the UK is limited due to low geothermal heat flux, as reported in the literature review. The average heat flux is ~ 50W/m, and thermal conductivity ~2.1W/mK; this results in marginal heat gradient of ~20K per 1km. Assuming a average annual air temperature of 10°C, the naturally occurring temperature will only be 30°C. By utilising waste or spare capacity heat from power stations heat can be stored in “dry” rock formations using engineered fractures. This would increase the possible application of geological heat storage further to those areas which do not have an underlying aquifer system.
4	Heat Transmission - Limited opportunities for IP generation is anticipated although possible opportunities may be identified to reduce installation costs and programme.
5	Local Network Distribution - Limited opportunities for IP generation is anticipated due to the wide spread deployment of district heating. Possibilities are limited to installation techniques that will reduce time and cost, and operational optimisation software that balances diurnal and seasonal storage, and supplementary heating.

15 Project Delivery Process

15.1 Review of Industry Capacity and Gap analysis

In order to assess the industry's capacity to deliver the scheme it is necessary to assess the various facets associated with the project life-cycle. It is also evident that industry capacity will be inherently dependent on the scale of the overall scheme and macro-programming of projects across the country. Setting the latter aspects and dependencies aside, the key facets relating to delivery are discussed below:

15.1.1 Professional Services

The first facet relates to the front-end client interface and provision of the required professional services. Upon review of the construction industry's capacity and overall capability in this sector, it is anticipated that a skills shortage problem would inevitably arise. The professional services industry is not geared up for a mass engagement of this kind.

Within the UK, there are a series of knowledge and skills hubs scattered around the consulting sector and various academic establishments. However, the knowledge base, capacity and capability are not coordinated in a manner required in a commercial environment. The ability of this network of hubs to deliver projects within a scheme of this scale is certainly not proven. Further afield, a limited degree of reliance can be placed on expertise across Europe and elsewhere, where geological heat storage schemes have been explored to a greater extent.

Based on preliminary high level research undertaken within the construction sector, many consultants are developing their expertise across related sectors such as ground source energy. It is anticipated that in the short to medium term, the construction sector will pursue and enhance the required skills and project experience to tackle heat storage in a coordinated commercially viable fashion. Cross-industry learning and skills exchange may also feed into this developmental process.

It is recommended that client bodies consider quality assurance and design management aspects. These will be strongly dependent on the particular forms of procurement adopted. Independent Category 3 checking should be considered and regarded as a necessity throughout the design process. Client bodies should also consider the establishment of an expert panel or steering group (or equivalent entity) which could potentially adopt a technical review and assurance role.

15.1.2 Construction Capacity

The second facet relates to the construction sector's ability to meet the heat storage scheme delivery demands. Specifically tailored ground investigation is a fundamental consideration which will have a direct impact on scheme delivery. Based on a preliminary review of the industry sector, combined with Buro Happold's experience in this field, it is expected that specialist ground investigation and drilling contractors will be able to meet the demands which may arise from the scheme. Advanced laboratory testing could be supported by both commercial laboratories and academic/research establishments. Furthermore, skills and capacity can be borrowed from parallel industries.

With regards to the capacity of the civil engineering and MandE engineering construction sectors, it is considered that a number of large UK contractors would be in a position to undertake the proposed scheme. The launch of a scheme of this scale would obviously attract significant interest within the construction sector. This would inherently ensure competitiveness. In view of the specialist nature of the various elements, the scheme may attract construction management and management contracting specialists who would procure specific (specialist) trade contractor packages as part of the holistic delivery process.

Based on industry trends and Buro Happold's experience, it is envisaged that the heat storage scheme would potentially attract significant interest from large contractors from across Europe.

15.1.3 Operation and Maintenance

The third facet relates to operation. Operational management will require expertise at various levels of seniority and technical standing. Professionals from engineering, energy and power sectors will require specific training and development relevant to the nature of the proposed heat storage scheme. The operational management arrangements, systems and structure will be dependent on the adopted forms of procurement.

It is proposed that operational systems and procedures include appropriate benchmarking protocols and performance indicator assessments in order to continuously review efficiency and inform whole-life-cycle analysis. It is strongly recommended that as part of operational verification of completed projects, the performance of the heat storage aquifers and geological strata be monitored. The monitoring data should inform ongoing design development of further projects part of the heat storage scheme. The data gathering process should be coordinated and fed into developing design guides and standards.

15.2 Review scheme delivery process and options for procurement

This section includes a review of the following:

- Single Project Delivery Process
- Design and Installation Contractual Options
- Procurement Funding Options

15.2.1 Single Project Delivery Process

Suggested key stages are shown in Table 53 below.

Table 53 Single Project Delivery Process

Stage	Outline
Stage 1 Stakeholder	Stakeholder Consultation (early engagement, continued throughout the project as required)
Stage 2 Desktop Study	Geological/ Hydrogeological Geotechnical/Geochemical Spatial Review Supply - Power Station Retrofit Technical Review Demand – Heat Distribution Network and confirmation of heat connection nodes EA Liaison Identification of project risks
Stage 3 Testing *Note: Phase 3 Testing from pilot studies not completed*	Testing Phase 1 (refer to 3.3. Pilot Studies)
	Testing Phase 2 (refer to 3.3. Pilot Studies) Phase 3 testing as part of installing first ATES module (see 3.3 Pilot studies)
Stage 4 Well field Completion	Including horizontal pipework, permanent pump arrangements, primary energy station building, ATES/BTES plant room, plant room installation. Expansion by modular design will be completed in parallel to Stage 5.
Stage 5 Heat Transmission Construction	Phase 1 – Secondary energy station building connection; serving local distribution for agglomeration IDs 1, 2, 3 etc Phase 2 – Secondary energy station building connection; serving local distribution for agglomeration 10, 11 , 12 Phase 3 – Secondary energy station building connection; serving local distribution for agglomeration IDs 20, 21 , 22 Phase 4 etc.
Stage 6 Heat Take-off Plant Conversion	Low Temperature BTES and ATES: to occur during minor refurbishment or servicing of power station Medium Temperature ATES: To occur during major refurbishment or replacement of power station
Stage 7 Operation Year 1 (Connection to Phase 1 Agglomerations)	System Preconditioning (over injection) Water Treatment Optimisation Environmental Monitoring Feedback Optimisation Phase 3 pilot project monitoring wells and tests to be further reviewed during the first year
Stage 8 Operation Year 2 (Connection to Phase 2 Agglomerations)	Further system preconditioning Environmental Monitoring Feedback Optimisation
Stage 9 Operation Year 3 (Connection to Phase 3 Agglomerations)	Further system preconditioning Environmental Monitoring Feedback Optimisation
Stage 10 Operation Year 4	System reaches steady state *Retained processes:* 1. Maintenance regime for system (including pumps, valves, water treatment plant etc.) 2. Environmental Monitoring

15.2.2 Procurement Process

Table 54 provides a high level review of some of the most common procurement processes and advantages/ disadvantages. During the last phase and formal write up the project team will look to review both procurement and funding opportunities in light of the final findings of the study.

Table 54 Design and Installation Contractual Options (Pilot phases completed)

Method	Advantages	Disadvantages
Traditional	Suited to complexity and bespoke nature of each installation. Suited as efficiency and successful operation of system is paramount Cost and Programme Certainty	Slower deployment High Professional Indemnity Insurance for specialist input
Possible Application	*Could be used for first wave of projects possibly with a Two stage tender to enable specialist contractor input. For future projects; outline design, testing and interpretation could still be retained by non-contractor design team, i.e. a form of "Develop and Construct".*	
Design and Build	Faster track to enable quicker deployment approach. Could use the Energy Supply Company (ESCo) model.	Not suited to initial non-commoditised design and installation, and complexity of system design. Detailed design could be compromised and/or costs increase significantly if project scope and specification is not accurate.
Possible application	*Could be used for commoditised installations once testing phase has been completed.*	
Management Contracting	Quick Deployment Suited to complex installation Contractor can engage with the design team from day one.	Lack of cost certainty until project is near completion – maybe not suited to public sector investment. Experienced team is needed which maybe difficult to procure due to nature of installation.
Possible application	*Not recommended*	

15.2.3 Funding Options

A select number of funding options have been considered in Table 35. For the initial installations, public finance is recommended to allow staged development and to ensure the programme is maintained prior to operation and revenue return.

Table 55 Procurement Funding Options

Method	Advantages	Disadvantages
Pure public investment This is the preferred option for the first projects	Public sector retains ownership of completed system Programme can be maintained without exposure to the private sector	Large public sector burden for large scale infrastructure. Will require long term commitment by successive governments to make a significant impact.
Private Finance Initiative (PFI)	Reduces public sector exposure to entire infrastructure capital investment. Reduces risk to public purse. Can include wrapped up operations contract once installation is complete.	May be difficult to attract investment for initial and future wave of installations due to unprecedented scale and cost. Less transparency for public sector and end consumer. Risk to project programme if relying on special purposes vehicle (SPV).
Energy Supply Company Model	Experience in energy market	Mass heat distribution maybe seen as direct competitor to more discrete CHP/ District Heating schemes which could be more profitable and less riskier.

15.3 Project Team Organogram

Figure 132 shows the outline design organogram. This will be further developed for the final report including delivery structure and additional proposed organograms for the testing, installation and operational phases. A traditional procurement method will be assumed for this process development.

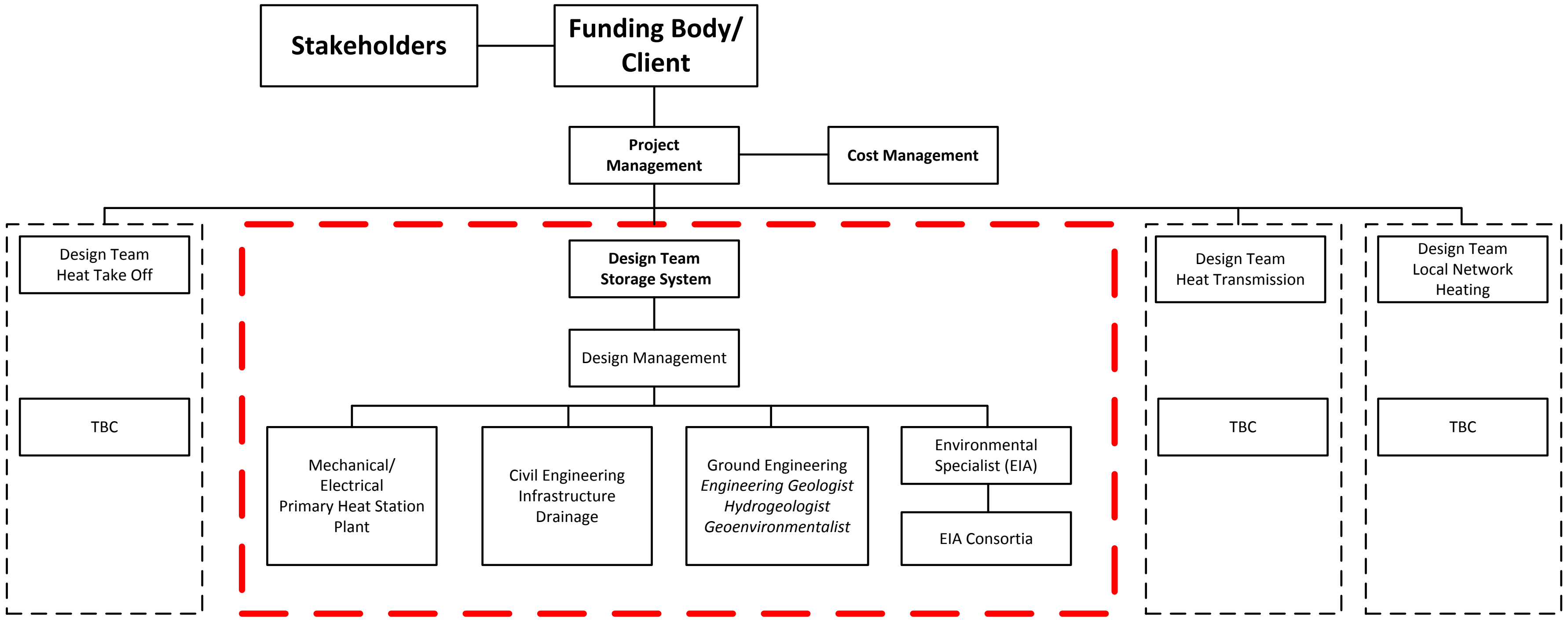

Figure 132 Outline Design Team Organogram

16 Conclusions and Scoping of Next Steps

The aim of this project was to "…. investigate the feasibility of storing large quantities of heat for long periods to meet a significant proportion (>10%) of UK winter heating load from heat stored during the summer."

The vision for the technological approach is to store and recover heat more cost effectively from constant running base-load generation than from part time peak shaving generation plant such as municipal boilers. The target cost for delivery of heat from storage to a district heat network is therefore less than £100/MWh(th).

To be able to conclude that an absolute percentage of UK winter heating can be provided from heat stored during the summer has proved difficult due to a number of factors:

1. Information on the utilisation of different power stations is not available, thus there is no robust basis for calculating the heat supply potential
2. There is a natural preference to deliver heat direct from power stations to end users without storage
3. There is not sufficiently detailed understanding of the district level district heating economics and viability
4. There is limited information on deep geological aquifers

What has been shown is that there is significant potential to store heat in shallow and deep sandstone aquifers, the latter providing the benefit of enabling higher temperature storage due to regulatory controls in shallow aquifers. The supply and demand ratio in any particular locality is crucial in forming the basis for seasonally storing heat. The cost of heat has shown to be competitive and nominally below the target cost stated above.

16.1 Conclusions

The main conclusions of the Research can be outlined as follows:

1. There are numerous examples of heat storage in Europe and Northern America although these systems are generally at a relatively low temperature and at a smaller *building* or *community* scale.
2. The preferred storage media are deep aquifers (200/300m bgl). The is because these deep aquifers are mostly brackish in nature and not as sensitive or regulated as shallow freshwater aquifers utilised for public potable supply.
3. The main design stage aspects include; accurate injection/ abstraction profiling, geological and hydrogeological analysis, suitable water treatment, assessing efficiency potential, groundwater flow, regulating control.
4. The most important operational aspects are water treatment, monitoring, heat injection, consumer heat use (which should match design assumptions), maximising efficiency and ongoing regulatory compliance.
5. Analytical and Numerical Modelling techniques to support the design and operation of systems are well developed and understood.
6. Economic district heating is a restricting factor as only a certain proportion of the UK is dense enough to allow for the economically viable heat networks at a local district level. Available spatial gas use data from DECC was used to formulate heat density maps for Great Britain with further supporting information for Northern Ireland. Using typical economic thresholds for district heating, 10% of the current UK gas fired heat demand is deemed economically viable with a further 44% deemed potentially viable in the future by connecting into less dens adjacent networks.
7. The regulating authorities in the UK are likely to object to the storage of higher temperature heat in near surface aquifers that are currently used for drinking water or other uses by existing licence holders. There is no clear benefit of high temperature (200^{o}C) option for a district heating network as medium heat (120^{o}C) is sufficient for required flow temperatures (80 – 85^{o}C). Furthermore, cost, technical problems and electrical power production losses are associated with high temperature systems. There are significant costs associated with low temperature (35^{o}C) systems (i.e. requirements for larger diameter pipework and heat pumps) which do not apply to medium heat systems.
8. As direct heat provision is preferred to storing in the ground prior to heat delivery, some locations show poor potential for geological storage. In these locations, potential heat supply is much higher than local demand throughout the year so there is no benefit for seasonal storage. Similarly where heat supply is much lower than demand throughout the year some additional form of heat provision is needed either through conventional means or through the strategic development of additional combined heat and power. This dynamic between local heat supply and demand should be a leading factor in decision making for the siting of new heat and power generation.
9. The significant capital costs associated with the system are linked to the distance of the primary heat network from the power station to the nearby heat demand centre, the geological storage system and conventional back up plant.
10. Two pilot Studies are suggested to fully assess the design and operational characteristics for this scale and use of system. Each installation will require an extensive site investigation to develop and prove the potential at each location.
11. The multi – criteria analysis (MCA) methodology adopted for the district focussed analysis which considered the geological potential, nearby heat demand and proximity to a power station the number of districts in the UK showing either high or medium potential equated to 23%. This relates to approximately 10% of the UK total heat demand.
12. The Power Station MCA was biased towards the availability of preferred geological storage and the demand and supply ratio. At a distance of 25km, 12 of the UK's 52 large power stations (>500MW) show high or medium potential for geological heat storage. By increasing the primary heat network to 50km increases this number to 20 large power stations.

16.2 Scoping of the Next Steps

The following is a brief review of the suggested next steps following the completion of the study.

1. Consultation (Informal/ Formal)

   >Buro Happold Consortium retained to answer further queries on extent of study

2. Further Technical Review
   a. Power Station Heat Take off Review
   b. EIA Case Study Test (Environmental Impacts)
   c. EA Case Study Test (Regulatory)
   d. Laboratory Testing (Geotechnical, Water Chemistry and Treatment)
   e. Complete System Model (Linkage of Power Generation, Heat Storage and Distribution)
3. Procurement Review
   a. Relevant Government Bodies
   b. Independent Financial Analysis
4. High Level Market Test of system to 3 Main Contractors to test Industrial Capacity
5. High Level Stakeholder Engagement
   a. ETI Members
   b. Power Companies
   c. Local Authorities
   d. Policy Makers (DECC)
6. Confirm Site Selection and Pilot Study Development
7. Pilot Study Commencement

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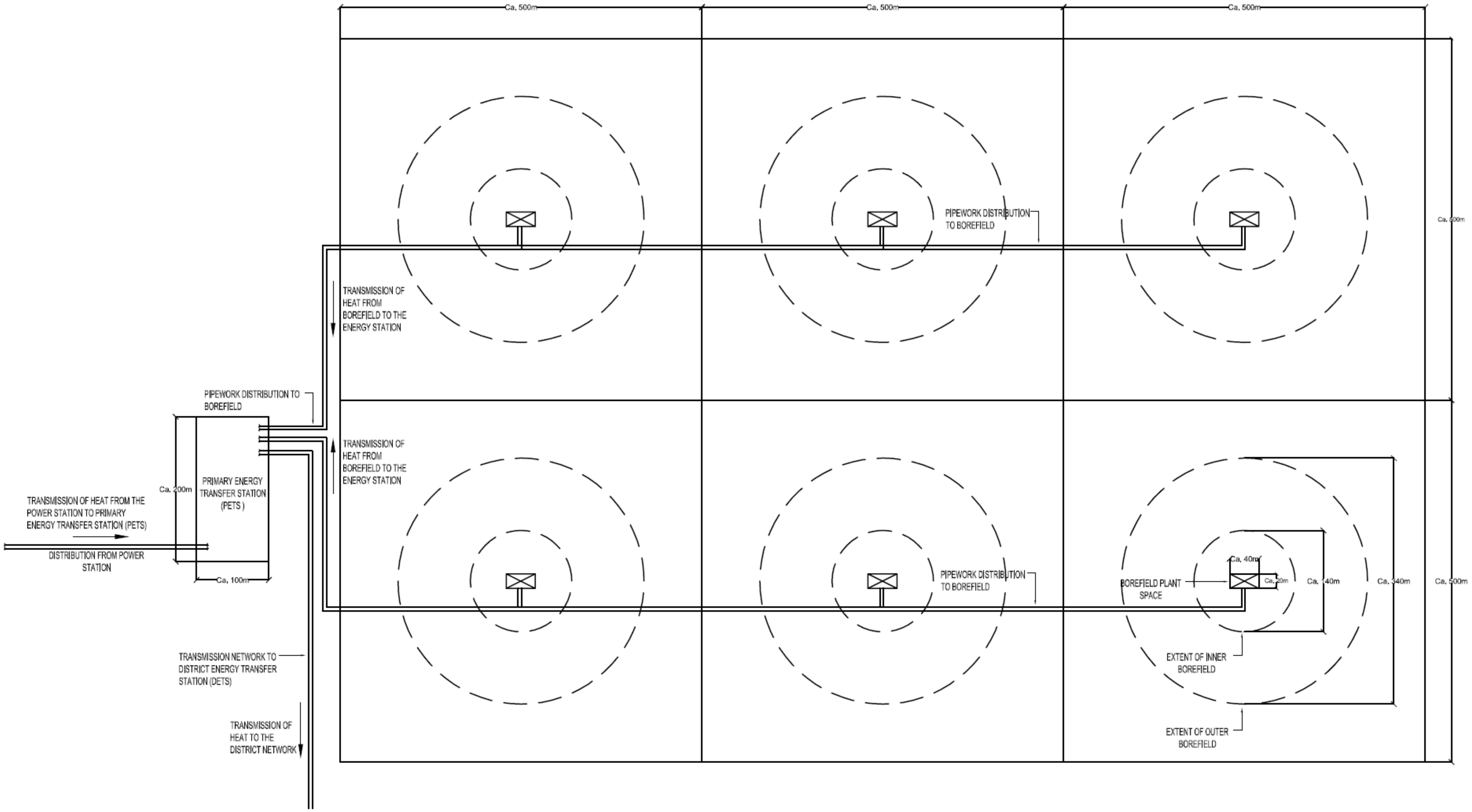
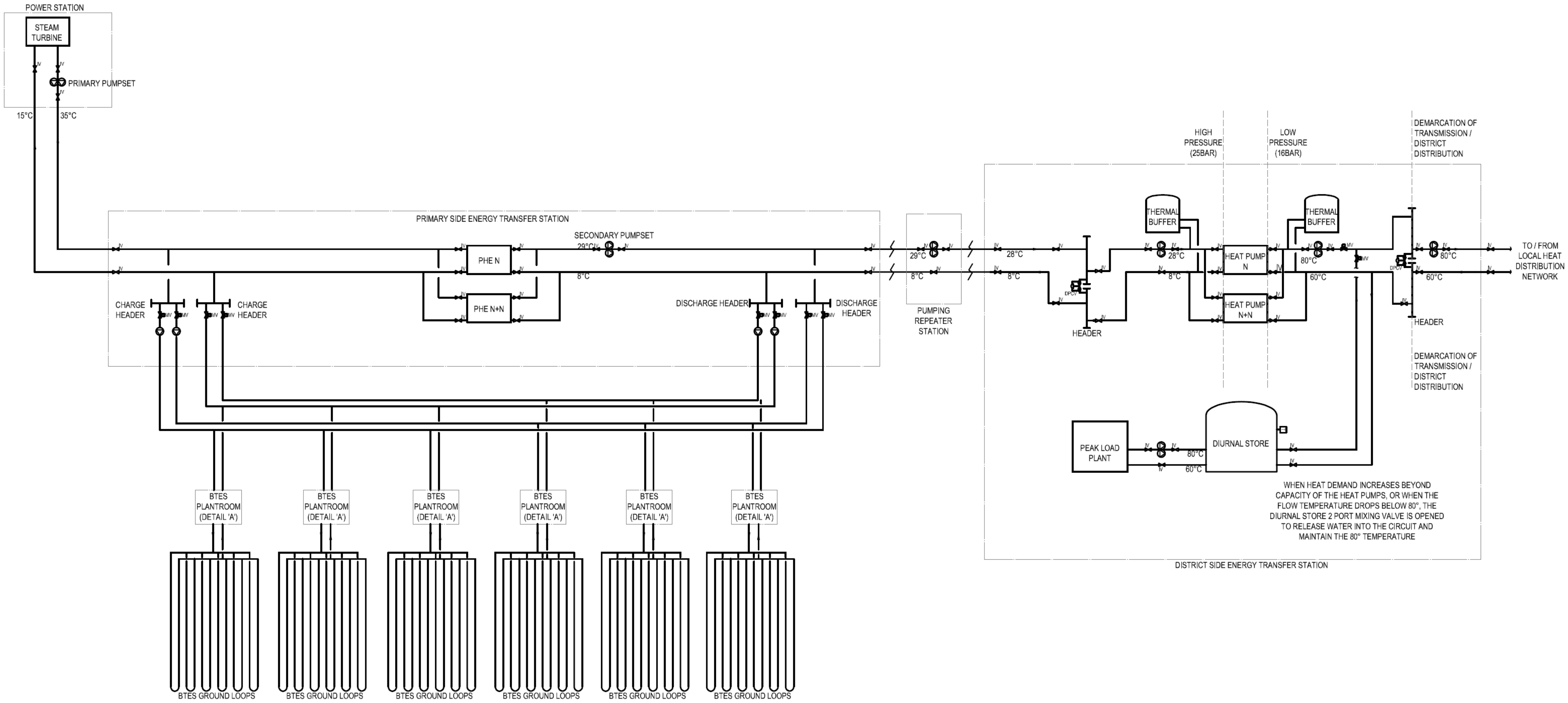
Appendix A Indicative System Schematics

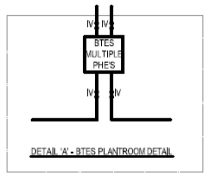
1. M100-01 – Indicative Borehole Field Layout
2. M700-01 - Option 1 - 35°C - 50km - 250MW
3. M700-02 - Option 2 - 120°C - 50km - 250MW

1. M100-01 – Indicative Borehole Field Layout



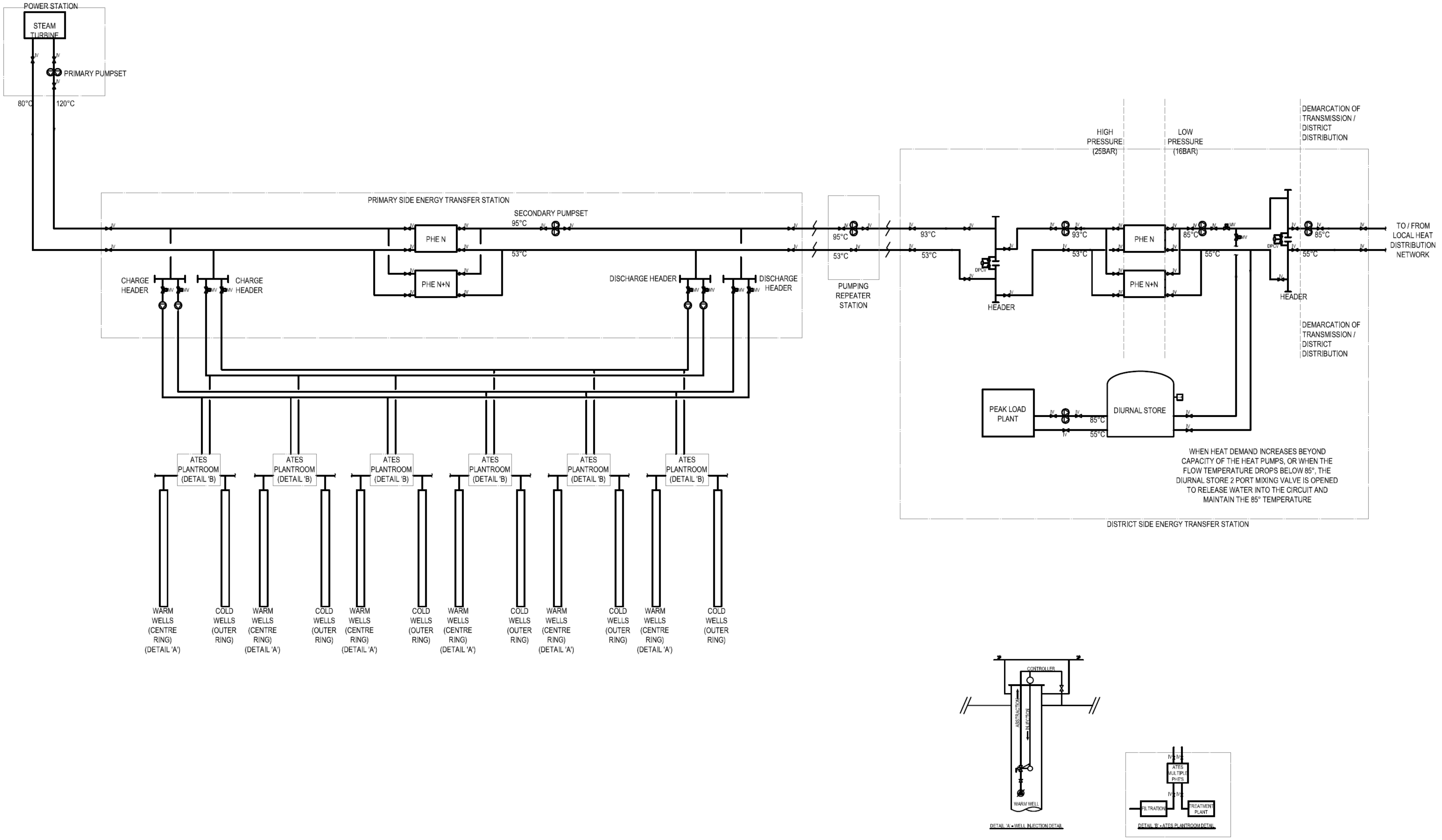
2. M700-01 - Option 1 - 35°C - 50km - 250MW





DETAIL 'A' - BTES PLANTROOM DETAIL

3. M700-02 - Option 2 - 120°C - 50km - 250MW



Appendix B – Bill of Quantities for Different Pilot Systems

Low Temperature Systems

Fiddler’s Ferry - **Very Low Temperature** - Bill of Quanities– Option 1A
Fiddler’s Ferry - **Very Low Temperature** - Bill of Quantities – Option 1B
Hartlepool Power Station – **Very Low Temperature** - Bill of Quanities – Option 2A
Hartlepool Power Station – **Very Low Temperature** - Bill of Quanities – Option 2B

Medium Temperature Systems

Fiddler’s Ferry - **Medium Temperature** - Bill of Quanities– Option 1A
Fiddler’s Ferry - **Medium Temperature** - Bill of Quanities– Option 1B
Hartlepool Power Station – **Medium Temperature** - Bill of Quanities – Option 2A
Hartlepool Power Station – **Medium Temperature** - Bill of Quanities – Option 2B

Fiddler’s Ferry - **Very Low Temperature** - Bill of Quanities– Option 1A

ETI - 028226
Outline schedule of plant items

LT - Option 1A

🟨 Plant section
🟦 Distribution section

Project lifecy	60	Years
Buildout yea	1	Years

Pumps	£	12,600,000	
Pipework	£	497,000,000	
Balance of plant	£	150,947,310	
Heat exchangers	£	9,000,000	
Ancillaries	£	23,552,748	
Building	£	40,500,000	
BTES	£	69,600,000	
Heat pumps	£	300,000,000	
Diurnal storage	£	158,054,954	
Controls	£	63,062,751	
Water treatment	£	6,000,000	Total
Land	£	810,000	£ 1,397,684,150
	£	66,556,388	

Section	Plant item	Plant capacity / selection criteria	Quantity / pipe length (m)	Cost / unit or metre length	Outline cost	Plant replacement (years)	Plant replacement (%)	Year 1	2
Power plant	Primary pumps	9449l/s @ 600kPa	2	500000	£ 1,000,000	15	0.8	£1,000,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 50,000	15	0.8	£50,000	£0
	Balance of plant (%)	30%			£ 315,000			£315,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 2000mm (3m/s flow)	1000	7000	£ 7,000,000			£7,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	36 No. units	36	250000	£ 9,000,000	15	0.8	£9,000,000	£0
	Circulation pumps	9449l/s @ 1600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
	Bypass loop pumps	2360l/s @ 400kPa	4	400000	£ 1,600,000	15	0.8	£1,600,000	£0
								£0	
					£ -			£0	
	Water treatment and pressurisation	Estimate	12	500000	£ 6,000,000	15	0.8	£6,000,000	£0
					£ -			£0	
	Bore hole land value		54	15000	£ 810,000			£810,000	
	BTES modules	12no. LT 200m depth	12	5800000	£ 69,600,000			£69,600,000	
	Valves & ancilliaries (%)	5%			£ 450,000	15	0.8	£450,000	£0
	Balance of plant (%)	30%			£ 5,400,000			£5,400,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Secondary energy transfer station (SETS) - District energy transfer station (DETS)					£ -			£0	
	Repeater pumps	9449/s @ 1600kPa	4	700000	£ 2,800,000	15	80	£2,800,000	£0
	Repeater pumps	9449/s @ 1600kPa	4	700000	£ 2,800,000	15	80	£2,800,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Pipe length	35km flow & return @ 2000mm (3m/s flow)	35000	7000	£ 245,000,000			£245,000,000	
	Pipe length	35km flow & return @ 2000mm (3m/s flow)	35000	7000	£ 245,000,000			£245,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Heat pumps	60 No. Ca. 25MW heat pumps	60	5000000	£ 300,000,000	15	0.8	£300,000,000	£0
	Circulation pumps (cold side]	9449 l/s @ 250kPa	2	500000	£ 1,000,000	15	0.8	£1,000,000	£0
	Circulation pumps (hot side)	25000l/s @ 1600kPa	2	1000000	£ 2,000,000	15	0.8	£2,000,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Diurnal storage vessel	m3 storage	1579050	100	£ 157,904,954	15	0.8	£157,904,954	£0
								£0	
								£0	
								£0	
								£0	
	Valves & ancilliaries (%)	5%			£ 23,052,748	15	0.8	£23,052,748	£0
	Balance of plant (%)	30%			£ 145,232,310			£145,232,310	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	1,268,065,012			1,268,065,012	£0
			5%	Total Inc. Controls @ 5%	1,331,468,262			1,331,468,262	
			5%	Total Inc. Testing @ 5%	1,398,041,675			1,398,041,675	
				Total CAPEX inc. Replacement (£)				**1,398,041,675**	**£0**

		Staff	1950000	1950000
		Pumping cost	59149110	59149110
		Maintenance cost @0.5% CAPEX	£6,340,325.06	£6,340,325.06
£/MwhE	100	Heat pump electrical input	404,458,288	404,458,288
		Total OPEX (£)	**471,897,722**	**471,897,722**
		Total CAPEX + OPEX (£)	**1,869,939,398**	**471,897,722**
Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**	**£13,932,543,081**	
Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**	**£7,420,698,633**	
		Total heat sales (Mwh)		14,560,498
		Discounted heat sales (Mwh) (Discount rate 1)		13592381
		Discounted heat sales (Mwh) (Discount rate 2)		12483280
		Total discounted heat sales (Mwh) (Discount rate 1)	**349139646**	
		Total discounted heat sales (Mwh) (Discount rate 2)	**166726819**	
				Optimism Balance
		Cost per Mwh (£/Mwh) (Discount rate 1)	**£39.91**	**£66.24**
		Cost per Mwh (£/Mwh) (Discount rate 2)	**£44.51**	**£73.88**

Fiddler’s Ferry - **Very Low Temperature** - Bill of Quantities – Option 1B

ETI - 028226
Outline schedule of plant items

LT - Option12B

🟨 Plant section
🟦 Distribution section

Project lifecy 60 Years
Buildout yea 1 Years

Pumps	£	26,600,000		
Pipework	£	1,834,000,000		
Balance of plant	£	717,684,619		
Heat exchangers	£	17,500,000		
Ancillaries	£	113,113,432		
Building	£	40,500,000		
BTES	£	104,400,000		
Heat pumps	£	1,800,000,000		
Diurnal storage	£	444,668,631		
Controls	£	255,413,834		
Water treatment	£	9,000,000	Total	
Land	£	810,000	£	5,631,875,041
	£	268,184,526		

CAPEX						OPEX			
						Plant replacement (years)	Plant replaceme nt (%)	Year	
Section	Plant item	Plant capacity / selection criteria	Quantity / pipe length (m)	Cost / unit or metre length	Outline cost			1	2
Power plant	Primary pumps	8500l/s @ 600kPa	4	600000	£ 2,400,000	15	0.8	£2,400,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 120,000	15	0.8	£120,000	£0
	Balance of plant (%)	30%			£ 756,000			£756,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 2000mm (3m/s flow)	1000	7000	£ 7,000,000			£7,000,000	
	Pipe length	1km flow & return @ 2000mm (3m/s flow)	1000	7000	£ 7,000,000			£7,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	70 No. units	70	250000	£ 17,500,000	15	0.8	£17,500,000	£0
	Circulation pumps	19000l/s @ 1600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
	Bypass loop pumps	4750l/s @ 400kPa	4	400000	£ 1,600,000	15	0.8	£1,600,000	£0
								£0	
					£ -			£0	
	Water treatment and pressurisation	Estimate	18	500000	£ 9,000,000	15	0.8	£9,000,000	£0
					£ -			£0	
	Bore hole land value		54	15000	£ 810,000			£810,000	
	BTES modules	18no. LT 200m depth	18	5800000	£ 104,400,000			£104,400,000	
	Valves & ancilliaries (%)	5%			£ 600,000	15	0.8	£600,000	£0
	Balance of plant (%)	30%			£ 8,850,000			£8,850,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Secondary energy transfer station (SETS) - District energy transfer station (DETS)					£ -			£0	
	Repeater pumps	8500/s @ 2500kPa - 5 stations	10	900000	£ 9,000,000	15	80	£9,000,000	£0
	Repeater pumps	8500/s @ 2500kPa - 5 stations	10	900000	£ 9,000,000	15	80	£9,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Pipe length	130km flow & return @ 2000mm (3m/s flow)	130000	7000	£ 910,000,000			£910,000,000	
	Pipe length	130km flow & return @ 2000mm (3m/s flow)	130000	7000	£ 910,000,000			£910,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Heat pumps	360 No. Ca. 25MW heat pumps	360	5000000	£ 1,800,000,000	15	0.8	£1,800,000,000	£0
	Circulation pumps (cold side	19000 l/s @ 250kPa	2	600000	£ 1,200,000	15	0.8	£1,200,000	£0
	Circulation pumps (hot side)	25000l/s @ 1600kPa	2	1000000	£ 2,000,000	15	0.8	£2,000,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Diurnal storage vessel	storage	4445186	100	£ 444,518,631	15	0.8	£444,518,631	£0
								£0	
								£0	
								£0	
								£0	
	Valves & ancilliaries (%)	5%			£ 112,393,432	15	0.8	£112,393,432	£0
	Balance of plant (%)	30%			£ 708,078,619			£708,078,619	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	5,108,276,681			5,108,276,681	£0
			5%	Total Inc. Controls @ 5%	5,363,690,515			5,363,690,515	
			5%	Total Inc. Testing @ 5%	5,631,875,041			5,631,875,041	
				Total CAPEX inc. Replacement (£)				**5,631,875,041**	**£0**

		Staff	1950000	1950000
		Pumping cost	141814326	141814326
		Maintenance cost @0.5% CAPEX	£25,541,383.40	£25,541,383.40
£/MwhE	100	Heat pump electrical input	1,138,591,538	1,138,591,538
		Total OPEX (£)	**1,307,897,248**	**1,307,897,248**
		Total CAPEX + OPEX (£)	**6,939,772,288**	**1,307,897,248**
Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**	**£41,472,106,012**	
Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**	**£22,602,733,676**	
		Total heat sales (Mwh)		40,989,295
		Discounted heat sales (Mwh) (Discount rate 1)		38263946
		Discounted heat sales (Mwh) (Discount rate 2)		35141714
		Total discounted heat sales (Mwh) (Discount rate 1)	**982863891**	
		Total discounted heat sales (Mwh) (Discount rate 2)	**469353087**	
				Optimism Balance
		Cost per Mwh (£/Mwh) (Discount rate 1)	£42.20	£70.04
		Cost per Mwh (£/Mwh) (Discount rate 2)	£48.16	£79.94

Hartlepool Power Station – **Very Low Temperature** - Bill of Quanities – Option 2A

ETI - 028226
Outline schedule of plant items

LT - Option 2A

🟨	Plant section
🟦	Distribution section
Project lifecy	60 Years
Buildout yea	1 Years

Pumps	£	6,800,000		
Pipework	£	84,000,000		
Balance of plant	£	92,835,137		
Heat exchangers	£	3,500,000		
Ancillaries	£	14,588,117		
Building	£	40,500,000		
BTES	£	69,600,000		
Heat pumps	£	240,000,000		
Diurnal storage	£	39,762,338		
Controls	£	29,919,780		
Water treatment	£	6,000,000	Total	
Land	£	810,000	£	659,731,140
	£	31,415,769		

CAPEX						OPEX			
						Plant replacement (years)	Plant replacement (%)	Year	
Section	Plant item	Plant capacity / selection criteria	Quantity / pipe length (m)	Cost / unit or metre length	Outline cost			1	2
Power plant	Primary pumps	3600l/s @ 600kPa	2	400000	£ 800,000	15	0.8	£800,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 40,000	15	0.8	£40,000	£0
	Balance of plant (%)	30%			£ 252,000			£252,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 1300mm (3m/s flow)	1000	4000	£ 4,000,000			£4,000,000	
								£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	14 No. units	14	250000	£ 3,500,000	15	0.8	£3,500,000	£0
	Circulation pumps	3600l/s @ 1600kPa	2	400000	£ 800,000	15	0.8	£800,000	£0
	Bypass loop pumps	900l/s @ 400kPa	4	300000	£ 1,200,000	15	0.8	£1,200,000	£0
								£0	
					£ -			£0	
	Water treatment and pressurisation	Estimate	12	500000	£ 6,000,000	15	0.8	£6,000,000	£0
					£ -			£0	
	Bore hole land value		54	15000	£ 810,000			£810,000	
	BTES modules	12no. LT 200m depth	12	5800000	£ 69,600,000			£69,600,000	
	Valves & ancilliaries (%)	5%			£ 400,000	15	0.8	£400,000	£0
	Balance of plant (%)	30%			£ 3,450,000			£3,450,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Secondary energy transfer station (SETS) - District energy transfer station (DETS)					£ -			£0	
	Repeater pumps	3600/s @ 1600kPa	2	400000	£ 800,000	15	80	£800,000	£0
						15	80	£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
								£0	
	Pipe length	20km flow & return @ 1300mm (3m/s flow)	20000	4000	£ 80,000,000			£80,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Heat pumps	48No. Ca. 25MW heat pumps	48	5000000	£ 240,000,000	15	0.8	£240,000,000	£0
	Circulation pumps (cold side)	3600 l/s @ 250kPa	2	600000	£ 1,200,000	15	0.8	£1,200,000	£0
	Circulation pumps (hot side)	7200l/s @ 1600kPa	2	1000000	£ 2,000,000	15	0.8	£2,000,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Diurnal storage vessel	storage	396123	100	£ 39,612,338	15	0.8	£39,612,338	£0
								£0	
								£0	
								£0	
								£0	
	Valves & ancilliaries (%)	5%			£ 14,148,117	15	0.8	£14,148,117	£0
	Balance of plant (%)	30%			£ 89,133,137			£89,133,137	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	**598,395,592**			**598,395,592**	**£0**
			5%	Total Inc. Controls @ 5%	**628,315,372**			**628,315,372**	
			5%	Total Inc. Testing @ 5%	**659,731,140**			**659,731,140**	
				Total CAPEX inc. Replacement (£)				**659,731,140**	**£0**
				Staff				1950000	1950000
				Pumping cost				12786271	12786271
				Maintenance cost @0.5% CAPEX				£2,991,977.96	£2,991,977.96
		£/MwhE	100	Heat pump electrical input				1,041,068	1,041,068
				Total OPEX (£)				**18,769,317**	**18,769,317**
				Total CAPEX + OPEX (£)				**678,500,457**	**18,769,317**
		Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**				**£1,508,804,278**	
		Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**				**£985,323,764**	
				Total heat sales (Mwh)					3,747,844
				Discounted heat sales (Mwh) (Discount rate 1)					3498653
				Discounted heat sales (Mwh) (Discount rate 2)					3213172
				Total discounted heat sales (Mwh) (Discount rate 1)				**89867875**	
				Total discounted heat sales (Mwh) (Discount rate 2)				**42915163**	
									Optimism Balance
				Cost per Mwh (£/Mwh) (Discount rate 1)				**£16.79**	**£27.87**
				Cost per Mwh (£/Mwh) (Discount rate 2)				**£22.96**	**£38.11**

Hartlepool Power Station – **Very Low Temperature** - Bill of Quanities – Option 2B

ETI - 028226
Outline schedule of plant items

LT - Option 2B

🟨	Plant section
🟦	Distribution section
Project lifecy	60 Years
Buildout yea	1 Years

Pumps	£	16,700,000		
Pipework	£	750,000,000		
Balance of plant	£	97,077,145		
Heat exchangers	£	10,000,000		
Ancillaries	£	14,958,118		
Building	£	40,500,000		
BTES	£	92,800,000		
Heat pumps	£	100,000,000		
Diurnal storage	£	183,462,364		
Controls	£	65,715,381		
Water treatment	£	8,000,000	Total	
Land	£	810,000	£	1,449,024,158
	£	69,001,150		

CAPEX						OPEX			
						Plant replaceme nt (years)	Plant replaceme nt (%)	Year	
Section	Plant item	Plant capacity / selection criteria	Quantity / pipe length (m)	Cost / unit or metre length	Outline cost			1	2
Power plant	Primary pumps	5500l/s @ 600kPa	4	500000	£ 2,000,000	15	0.8	£2,000,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 100,000	15	0.8	£100,000	£0
	Balance of plant (%)	30%			£ 630,000			£630,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 1600mm (3m/s flow)	1000	5000	£ 5,000,000			£5,000,000	
	Pipe length	1km flow & return @ 1600mm (3m/s flow)	1000	5000	£ 5,000,000			£5,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	40 No. units	40	250000	£ 10,000,000	15	0.8	£10,000,000	£0
	Circulation pumps	1100l/s @ 1600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
	Bypass loop pumps	275l/s @ 400kPa	4	300000	£ 1,200,000	15	0.8	£1,200,000	£0
								£0	
					£ -			£0	
	Water treatment and pressurisation	Estimate	16	500000	£ 8,000,000	15	0.8	£8,000,000	£0
					£ -			£0	
	Bore hole land value		54	15000	£ 810,000			£810,000	
	BTES modules	16no. LT 200m depth	16	5800000	£ 92,800,000			£92,800,000	
	Valves & ancilliaries (%)	5%			£ 530,000	15	0.8	£530,000	£0
	Balance of plant (%)	30%			£ 6,180,000			£6,180,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Secondary energy transfer station (SETS) - District energy transfer station (DETS)					£ -			£0	
	Repeater pumps	5500/s @ 2500kPa - 3 stations	6	750000	£ 4,500,000	15	80	£4,500,000	£0
	Repeater pumps	5500/s @ 2500kPa - 3 stations	6	750000	£ 4,500,000	15	80	£4,500,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Pipe length	74km flow & return @ 1600mm (3m/s flow)	74000	5000	£ 370,000,000			£370,000,000	
	Pipe length	74km flow & return @ 1600mm (3m/s flow)	74000	5000	£ 370,000,000			£370,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Heat pumps	20No. Ca. 25MW heat pumps	20	5000000	£ 100,000,000	15	0.8	£100,000,000	£0
	Circulation pumps (cold side)	11000 l/s @ 250kPa	2	600000	£ 1,200,000	15	0.8	£1,200,000	£0
	Circulation pumps (hot side)	2400l/s @ 1600kPa	2	950000	£ 1,900,000	15	0.8	£1,900,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Thermal buffer vessel	500m3 store	500	150	£ 75,000	15	0.8	£75,000	£0
	Diurnal storage vessel	storage	1833124	100	£ 183,312,364	15	0.8	£183,312,364	£0
								£0	
								£0	
								£0	
								£0	
	Valves & ancilliaries (%)	5%			£ 14,328,118	15	0.8	£14,328,118	£0
	Balance of plant (%)	30%			£ 90,267,145			£90,267,145	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	**1,314,307,627**			**1,314,307,627**	**£0**
			5%	Total Inc. Controls @ 5%	**1,380,023,008**			**1,380,023,008**	
			5%	Total Inc. Testing @ 5%	**1,449,024,158**			**1,449,024,158**	
				Total CAPEX inc. Replacement (£)				**1,449,024,158**	**£0**
				Staff				1950000	1950000
				Pumping cost				70686630	70686630
				Maintenance cost @0.5% CAPEX				£6,571,538.13	£6,571,538.13
		£/MwhE	100	Heat pump electrical input				4,693,403	4,693,403
				Total OPEX (£)				**83,901,571**	**83,901,571**
				Total CAPEX + OPEX (£)				**1,532,925,729**	**83,901,571**
		Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**				**£4,293,528,910**	
		Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**				**£2,662,390,570**	
				Total heat sales (Mwh)					16,896,250
				Discounted heat sales (Mwh) (Discount rate 1)					15772830
				Discounted heat sales (Mwh) (Discount rate 2)					14485811
				Total discounted heat sales (Mwh) (Discount rate 1)				**405147583**	
				Total discounted heat sales (Mwh) (Discount rate 2)				**193472637**	
									Optimism Balance
				Cost per Mwh (£/Mwh) (Discount rate 1)				**£10.60**	**£17.59**
				Cost per Mwh (£/Mwh) (Discount rate 2)				**£13.76**	**£22.84**

Fiddler’s Ferry - **Medium Temperature** - Bill of Quanities– Option 1A

ETI - 028226
Outline schedule of plant items

HT - 1A

Plant section
Distribution section

Project lifecy	60	Years
Buildout yea	1	Years

Pumps	£	5,800,000		
Pipework	£	360,000,000		
Balance of plant	£	89,054,288		
Heat exchangers	£	15,000,000		
Ancillaries	£	14,842,381		
Building	£	40,500,000		
BTES	£	63,600,000		
Heat pumps				
Diurnal storage	£	218,637,628		
Controls	£	40,842,215		
Water treatment	£	3,000,000	Total	
Land	£	810,000	£	894,690,839
	£	42,604,326		

CAPEX						OPEX			
						Plant replacement (years)	Plant replacement (%)	Year	
Section	Plant item	Plant capacity / selection criteria	Quantity / pipe length (m)	Cost / unit or metre length	Outline cost			1	2
Power plant	Primary pumps	11000/s @ 600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 70,000	15	0.8	£70,000	£0
	Balance of plant (%)	30%			£ 420,000			£420,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 1600mm (3m/s flow)	1000	5000	£ 5,000,000			£5,000,000	
	Pipe length	1km flow & return @ 1600mm (3m/s flow)	1000	5000	£ 5,000,000			£5,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	40 No. units (N+N)	40	250000	£ 10,000,000	15	0.8	£10,000,000	£0
	Circulation pumps	11000l/s @ 1600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
	Bypass loop pumps	2750l/s @ 400kPa	4	300000	£ 1,200,000	15	0.8	£1,200,000	£0
								£0	
	Water treatment and pressurisation		6	500000	£ 3,000,000	15	0.8	£3,000,000	£0
	Bore hole land value		54	15000	£ 810,000	15	0.8	£810,000	£0
	ATES modules	6no. HT 400m depth	6	10600000	£ 63,600,000	15	0.8	£63,600,000	£0
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 3,500,500	15	0.8	£3,500,500	£0
	Balance of plant (%)	30%			£ 21,003,000			£21,003,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Primary energy transfer station (PETS) - Secondary energy transfer station (SETS)					£ -			£0	
	Repeater pumps	11000/s @ 1600kPa	4	700000	£ 2,800,000	15	80	£2,800,000	£0
	Repeater pumps	11000/s @ 1600kPa	4	700000	£ 2,800,000	15	80	£2,800,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Pipe length	35km flow & return @ 1600mm (3m/s flow)	35000	5000	£ 175,000,000			£175,000,000	
	Pipe length	35km flow & return @ 1600mm (3m/s flow)	35000	5000	£ 175,000,000			£175,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	20 No. units (N+N)	20	250000	£ 5,000,000	15	0.8	£5,000,000	£0
	Circulation pumps (cold side]	11000 l/s @ 250kPa	2	300000	£ 600,000	15	0.8	£600,000	£0
	Circulation pumps (hot side)	11000l/s @ 1600kPa	2	600000	£ 1,200,000	15	0.8	£1,200,000	£0
	Diurnal storage vessel	m3 storage	2186376	100	£ 218,637,628	15	0.8	£218,637,628	£0
					£ -	15	0.8	£0	£0
					£ -				
					£ -				
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 11,271,881	15	0.8	£11,271,881	£0
	Balance of plant (%)	30%			£ 67,631,288			£67,631,288	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	816,844,298			£816,844,299	£0
			5%	Total Inc. Controls @ 5%	857,686,513			857,686,514	
			5%	Total Inc. Testing @ 5%	900,570,839			900,570,840	
				Total CAPEX inc. Replacement (£)				**900,570,840**	**£0**

		Staff	1950000	1950000
		Pumping cost	48285558	48285558
		Maintenance cost @0.5% CAPEX	£4,084,221.50	£4,084,221.50
£/MwhE	100	Lost electrical load	315,360,000	315,360,000
		Total OPEX (£)	**369,679,779**	**369,679,779**
		Total CAPEX + OPEX (£)	**1,270,250,619**	**369,679,779**
Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**	**£10,713,954,423**	
Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**	**£5,628,634,043**	
		Total heat sales (Mwh)		12,885,397
		Discounted heat sales (Mwh) (Discount rate 1)		12028656
		Discounted heat sales (Mwh) (Discount rate 2)		11047151
		Total discounted heat sales (Mwh) (Discount rate 1)	**308973138**	
		Total discounted heat sales (Mwh) (Discount rate 2)	**147545858**	
				Optimism Balance
		Cost per Mwh (£/Mwh)	**£34.68**	**£57.56**
		Cost per Mwh (£/Mwh)	**£38.15**	**£63.33**

Fiddler's Ferry - **Medium Temperature** - Bill of Quanities– Option 1B

ETI - 028226
Outline schedule of plant items

HT - 1B

🟨 Plant section
🟦 Distribution section

Project lifecy 60 Years

Buildout yea 1 Years

Pumps	£	25,800,000		
Pipework	£	1,310,000,000		
Balance of plant	£	228,089,200		
Heat exchangers	£	15,000,000		
Ancillaries	£	38,014,867		
Building	£	40,500,000		
BTES	£	127,200,000		
Heat pumps				
Diurnal storage	£	615,487,335		
Controls	£	120,345,070		
Water treatment	£	6,000,000	Total	
Land	£	810,000	£	2,653,608,795
	£	126,362,324		

CAPEX						Plant replacement (years)	Plant replacement (%)	Year	
Section	**Plant item**	**Plant capacity / selection criteria**	**Quantity / pipe length (m)**	**Cost / unit or metre length**	**Outline cost**			**1**	**2**
Power plant	Primary pumps	11000/s @ 600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 70,000	15	0.8	£70,000	£0
	Balance of plant (%)	30%			£ 420,000			£420,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 1600mm (3m/s flow)	1000	5000	£ 5,000,000			£5,000,000	
	Pipe length	1km flow & return @ 1600mm (3m/s flow)	1000	5000	£ 5,000,000			£5,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	40 No. units (N+N)	40	250000	£ 10,000,000	15	0.8	£10,000,000	£0
	Circulation pumps	11000l/s @ 1600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
	Bypass loop pumps	2750l/s @ 400kPa	4	300000	£ 1,200,000	15	0.8	£1,200,000	£0
								£0	
	Water treatment and pressurisation		12	500000	£ 6,000,000	15	0.8	£6,000,000	£0
	Bore hole land value		54	15000	£ 810,000	15	0.8	£810,000	£0
	ATES modules	12no. HT 400m depth	12	10600000	£ 127,200,000	15	0.8	£127,200,000	£0
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 6,830,500	15	0.8	£6,830,500	£0
	Balance of plant (%)	30%			£ 40,983,000			£40,983,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Primary energy transfer station (PETS) - Secondary energy transfer station (SETS)					£ -			£0	
	Repeater pumps	11000/s @ 2500kPa	10	1000000	£ 10,000,000	15	80	£10,000,000	£0
	Repeater pumps	11000/s @ 2500kPa	10	1000000	£ 10,000,000	15	80	£10,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Pipe length	130km flow & return @ 1600mm (3m/s flow)	130000	5000	£ 650,000,000			£650,000,000	
	Pipe length	130km flow & return @ 1600mm (3m/s flow)	130000	5000	£ 650,000,000			£650,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	20 No. units (N+N)	20	250000	£ 5,000,000	15	0.8	£5,000,000	£0
	Circulation pumps (cold side)	11000 l/s @ 250kPa	2	300000	£ 600,000	15	0.8	£600,000	£0
	Circulation pumps (hot side)	11000l/s @ 1600kPa	2	600000	£ 1,200,000	15	0.8	£1,200,000	£0
	Diurnal storage vessel	m3 storage	6154873	100	£ 615,487,335	15	0.8	£615,487,335	£0
					£ -	15	0.8	£0	£0
					£ -				
					£ -				
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 31,114,367	15	0.8	£31,114,367	£0
	Balance of plant (%)	30%			£ 186,686,200			£186,686,200	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	**2,406,901,402**			**£2,406,901,403**	**£0**
			5%	Total Inc. Controls @ 5%	**2,527,246,472**			**2,527,246,473**	
			5%	Total Inc. Testing @ 5%	**2,653,608,795**			**2,653,608,797**	
				Total CAPEX inc. Replacement (£)				**2,653,608,797**	**£0**
				Staff				1950000	1950000
				Pumping cost				48285558	48285558
				Maintenance cost @0.5% CAPEX				£12,034,507.01	£12,034,507.01
		£/MwhE	100	Lost electrical load				315,360,000	315,360,000
				Total OPEX (£)				**377,630,065**	**377,630,065**
				Total CAPEX + OPEX (£)				**3,031,238,862**	**377,630,065**
		Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**				**£13,853,929,472**	
		Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**				**£7,790,219,155**	
				Total heat sales (Mwh)					36,273,713
				Discounted heat sales (Mwh) (Discount rate 1)					33861899
				Discounted heat sales (Mwh) (Discount rate 2)					31098862
				Total discounted heat sales (Mwh) (Discount rate 1)				**869791054**	
				Total discounted heat sales (Mwh) (Discount rate 2)				**415356714**	
									Optimism Balance
				Cost per Mwh (£/Mwh)				**£15.93**	**£26.44**
				Cost per Mwh (£/Mwh)				**£18.76**	**£31.13**

Hartlepool Power Station – **Medium Temperature** - Bill of Quanities – Option 2A

ETI - 028226
Outline schedule of plant items

HT - 2A

Plant section
Distribution section

Project lifecy	60	Years
Buildout yea	1	Years

Pumps	£	7,400,000		
Pipework	£	84,000,000		
Balance of plant	£	39,047,356		
Heat exchangers	£	5,000,000		
Ancillaries	£	6,507,893		
Building	£	40,500,000		
BTES	£	63,600,000		
Heat pumps				
Diurnal storage	£	54,847,853		
Controls	£	15,235,655		
Water treatment	£	3,000,000	Total	
Land	£	810,000	£	335,946,195
	£	15,997,438		

CAPEX						OPEX			
						Plant replacement (years)	Plant replacement (%)	Year	
Section	Plant item	Plant capacity / selection criteria	Quantity / pipe length (m)	Cost / unit or metre length	Outline cost			1	2
Power plant	Primary pumps	2600/s @ 600kPa	2	500000	£ 1,000,000	15	0.8	£1,000,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 50,000	15	0.8	£50,000	£0
	Balance of plant (%)	30%			£ 300,000			£300,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 1200mm (3m/s flow)	1000	4000	£ 4,000,000			£4,000,000	
								£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	10 No. units (N+N)	10	250000	£ 2,500,000	15	0.8	£2,500,000	£0
	Circulation pumps	2600l/s @ 1600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
	Bypass loop pumps	650l/s @ 400kPa	4	300000	£ 1,200,000	15	0.8	£1,200,000	£0
								£0	
	Water treatment and pressurisation		6	500000	£ 3,000,000	15	0.8	£3,000,000	£0
	Bore hole land value		54	15000	£ 810,000	15	0.8	£810,000	£0
	ATES modules	6no. HT 400m depth	6	10600000	£ 63,600,000	15	0.8	£63,600,000	£0
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 3,500,500	15	0.8	£3,500,500	£0
	Balance of plant (%)	30%			£ 21,003,000			£21,003,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Primary energy transfer station (PETS) - Secondary energy transfer station (SETS)					£ -			£0	
	Repeater pumps	2600/s @ 1600kPa	2	1000000	£ 2,000,000	15	80	£2,000,000	£0
								£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
								£0	
	Pipe length	20km flow & return @ 1200mm (3m/s flow)	20000	4000	£ 80,000,000			£80,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	10 No. units (N+N)	10	250000	£ 2,500,000	15	0.8	£2,500,000	£0
	Circulation pumps (cold side)	2600 l/s @ 250kPa	2	300000	£ 600,000	15	0.8	£600,000	£0
	Circulation pumps (hot side)	2600l/s @ 1600kPa	2	600000	£ 1,200,000	15	0.8	£1,200,000	£0
	Diurnal storage vessel	m3 storage	548479	100	£ 54,847,853	15	0.8	£54,847,853	£0
					£ -	15	0.8	£0	£0
					£ -				
					£ -				
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 2,957,393	15	0.8	£2,957,393	£0
	Balance of plant (%)	30%			£ 17,744,356			£17,744,356	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	**304,713,102**			**£304,713,103**	**£0**
			5%	Total Inc. Controls @ 5%	**319,948,757**			**319,948,758**	
			5%	Total Inc. Testing @ 5%	**335,946,195**			**335,946,196**	
				Total CAPEX inc. Replacement (£)				**335,946,196**	**£0**
				Staff				1950000	1950000
				Pumping cost				9030334	9030334
				Maintenance cost @0.5% CAPEX				£1,523,565.51	£1,523,565.51
		£/MwhE	100	Lost electrical load				75,336,000	75,336,000
				Total OPEX (£)				**87,839,899**	**87,839,899**
				Total CAPEX + OPEX (£)				**423,786,095**	**87,839,899**
		Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**				**£2,866,497,252**	
		Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**				**£1,521,895,932**	
				Total heat sales (Mwh)					3,316,676
				Discounted heat sales (Mwh) (Discount rate 1)					3096153
				Discounted heat sales (Mwh) (Discount rate 2)					2843515
				Total discounted heat sales (Mwh) (Discount rate 1)				**79529093**	
				Total discounted heat sales (Mwh) (Discount rate 2)				**37978021**	
									Optimism Balance
				Cost per Mwh (£/Mwh)				**£36.04**	**£59.83**
				Cost per Mwh (£/Mwh)				**£40.07**	**£66.52**

Hartlepool Power Station – **Medium Temperature** - Bill of Quanities – Option 2B

ETI - 028226
Outline schedule of plant items

HT - 2B

🟨 Plant section
🟦 Distribution section

Project lifecy 60 Years
Buildout yea 1 Years

Pumps	£	17,800,000		
Pipework	£	608,000,000		
Balance of plant	£	118,838,136		
Heat exchangers	£	12,500,000		
Ancillaries	£	19,806,356		
Building	£	40,500,000		
BTES	£	127,200,000		
Heat pumps				
Diurnal storage	£	253,817,119		
Controls	£	60,263,581		
Water treatment	£	6,000,000	Total	
Land	£	810,000	£	1,328,811,951
	£	63,276,760		

CAPEX						OPEX			
						Plant replacement (years)	Plant replacement (%)	Year	
Section	Plant item	Plant capacity / selection criteria	Quantity / pipe length (m)	Cost / unit or metre length	Outline cost			1	2
Power plant	Primary pumps	11000/s @ 600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 70,000	15	0.8	£70,000	£0
	Balance of plant (%)	30%			£ 420,000			£420,000	
	Building (m2)		500	1000	£ 500,000			£500,000	
Power plant - Primary energy transfer station (PETS)	Pipe length	1km flow & return @ 1200mm (3m/s flow)	1000	4000	£ 4,000,000			£4,000,000	
	Pipe length	1km flow & return @ 1200mm (3m/s flow)	1000	4000	£ 4,000,000			£4,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Land Costs				£ -			£0	
Primary energy transfer station (PETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	40 No. units (N+N)	40	250000	£ 10,000,000	15	0.8	£10,000,000	£0
	Circulation pumps	11000l/s @ 1600kPa	2	700000	£ 1,400,000	15	0.8	£1,400,000	£0
	Bypass loop pumps	2750l/s @ 400kPa	4	300000	£ 1,200,000	15	0.8	£1,200,000	£0
								£0	
	Water treatment and pressurisation		12	500000	£ 6,000,000	15	0.8	£6,000,000	£0
	Bore hole land value		54	15000	£ 810,000	15	0.8	£810,000	£0
	ATES modules	12no. HT 400m depth	12	10600000	£ 127,200,000	15	0.8	£127,200,000	£0
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 6,830,500	15	0.8	£6,830,500	£0
	Balance of plant (%)	30%			£ 40,983,000			£40,983,000	
	Building (m2)		20000	1000	£ 20,000,000			£20,000,000	
Primary energy transfer station (PETS) - Secondary energy transfer station (SETS)					£ -			£0	
	Repeater pumps	5500/s @ 2500kPa	6	1000000	£ 6,000,000	15	80	£6,000,000	£0
	Repeater pumps	5500/s @ 2500kPa	6	1000000	£ 6,000,000	15	80	£6,000,000	
					£ -			£0	
					£ -			£0	
					£ -			£0	
	Pipe length	75km flow & return @ 1200mm (3m/s flow)	75000	4000	£ 300,000,000			£300,000,000	
	Pipe length	75km flow & return @ 1200mm (3m/s flow)	75000	4000	£ 300,000,000			£300,000,000	
	Land Costs							£0	
District energy transfer station (DETS)					£ -			£0	
	Plate heat exchangers (limited to 550 kg/s ea.)	10 No. units (N+N)	10	250000	£ 2,500,000	15	0.8	£2,500,000	£0
	Circulation pumps (cold side)	2600 l/s @ 250kPa	2	300000	£ 600,000	15	0.8	£600,000	£0
	Circulation pumps (hot side)	2600l/s @ 1600kPa	2	600000	£ 1,200,000	15	0.8	£1,200,000	£0
	Diurnal storage vessel	m3 storage	2538171	100	£ 253,817,119	15	0.8	£253,817,119	£0
					£ -	15	0.8	£0	£0
					£ -				
					£ -				
					£ -			£0	
	Valves & ancilliaries (%)	5%			£ 12,905,856	15	0.8	£12,905,856	£0
	Balance of plant (%)	30%			£ 77,435,136			£77,435,136	
	Building		20000	1000	£ 20,000,000			£20,000,000	
				Total	**1,205,271,611**			**£1,205,271,612**	**£0**
			5%	Total Inc. Controls @ 5%	**1,265,535,191**			**1,265,535,192**	
			5%	Total Inc. Testing @ 5%	**1,328,811,951**			**1,328,811,952**	
				Total CAPEX inc. Replacement (£)				**1,328,811,952**	**£0**
				Staff				1950000	1950000
				Pumping cost				73108332	73108332
				Maintenance cost @0.5% CAPEX				£6,026,358.06	£6,026,358.06
		£/MwhE	100	Lost electrical load				341,640,000	341,640,000
				Total OPEX (£)				**422,724,690**	**422,724,690**
				Total CAPEX + OPEX (£)				**1,751,536,642**	**422,724,690**
		Discount rate 1	3.50%	**NPV CAPEX + OPEX (Discount rate 1)**				**£12,889,662,002**	
		Discount rate 2	8.00%	**NPV CAPEX + OPEX (Discount rate 2)**				**£6,836,370,542**	
				Total heat sales (Mwh)					14,952,434
				Discounted heat sales (Mwh) (Discount rate 1)					13958257
				Discounted heat sales (Mwh) (Discount rate 2)					12819302
				Total discounted heat sales (Mwh) (Discount rate 1)				**358537684**	
				Total discounted heat sales (Mwh) (Discount rate 2)				**171214723**	
									Optimism Balance
				Cost per Mwh (£/Mwh)				**£35.95**	**£59.68**
				Cost per Mwh (£/Mwh)				**£39.93**	**£66.28**

Feasibility of Geological Heat Storage in the UK

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