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GEOTHERMAL ENERGY CHALLENGE

GUARDBRIDGE GEOTHERMAL TECHNOLOGY DEMONSTRATOR PROJECT

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Robinson, R.A.J., Townsend, P., Steen, P., Barron, H. Abesser, C.A., Muschamp, H., McGrath, I., and Todd, I. (2016). Geothermal Energy Challenge Fund: the Guardbridge Geothermal Technology Project. 105 pp.

GEOTHERMAL ENERGY CHALLENGE EXECUTIVE SUMMARY

This feasibility study investigates whether a geothermal district heating system, which accesses Hot Sedimentary Aquifer (HSA) resources underlying a brownfield site at Guardbridge in northeast Fife, can be developed in a cost-effective manner. This project's scope is to assess the available geological information and estimate the hot saline aquifer heat supply, calculate the current heat demand at the Guardbridge site, Guardbridge village, and the nearby towns of Leuchars and Balmullo, and to incorporate future Guardbridge development plans (provided by the University of St Andrews) and anticipated growth in housing stock (from Fife Council) to estimate future heat demand. The capital, maintenance and repair costs for the geothermal well and designed district heating network are used to develop economic models for a number of district heat network scenarios. A key aspect of this study is an evaluation of the opportunities to cost effectively de-risk deep geothermal exploration in Central Scotland, and to outline the potential for developing geological heat storage systems. The study identifies the key legislative and environmental issues, risks and uncertainties associated with any exploration and production, involves stakeholder engagement, and makes recommendations for a Phase 2 stage for geothermal heat development at Guardbridge.

Two of the key outputs from this feasibility study will be an economic model and business case based on different heat demand options, and an optimised model of well design based on different exploration strategies. Both are transferable to similar operations at other geothermal sites. The key objectives are therefore to:

(a) design a geothermal well that will be drilled in Phase 2 of the project, and secure valuable information on Fife regional sub-surface geology and geothermal properties of the primary aquifer,

(b) explore how advanced drilling techniques, such as directional drilling, can be deployed to improve geothermal recovery,

(c) demonstrate how a geothermal system can integrate with an existing biomass heating installation to optimise both schemes and provide a district heat network for on-site industries and the local community,

(d) evaluate the potential for storage of seasonal heat energy in the subsurface (a first in Scotland), and

(e) assess the relative merits of water treatment and on-site recycling, re-injection or disposal to sea.

A regional geological model was constructed using available data from the British Geological Survey, published data and academic theses. The sub-surface geology was interpreted from surface geology and extrapolating the local behaviour of geological structures into the Guardbridge area. Modelling the geology involved defining the orientation and width of a natural fault zone, which could be a significant influence on the behaviour of the Hot Sedimentary Aquifers. The rock units of interest in this study are the Upper Devonian Scone Sandstone, Glenvale Sandstone, Knox Pulpit and Kinnesswood formations, and the latter two units are previously identified as having the highest potential to be highly productive aquifers. The presence of a major fault near the Guardbridge site means that the target aquifers are at very different depths on either side of the fault. The report therefore investigates and evaluates three well options to target the different aquifers at the varying depths on either side of the fault.

Hydrogeological modelling was conducted using FEFLOW® to evaluate the behaviour of the fault on fluid flow rates, and to predict the necessary conductivities to produce reasonable, economic and sustainable rates of fluid extraction. Although not an accurate model of the Guardbridge site, and limited by a significant lack of data constraining the important parameters, the flow simulations suggest that fracture permeability in the aquifers and underlying rocks is needed to sustain the flows recommended by this study, and re-injection would be required if a producing well was to be sustainable over many decades.

Regionally developed rock quality predictors have been used to estimate the permeability and temperature of the target aquifer intervals in the three selected well options at, or near, Guardbridge. Oil field well simulation tools have been used to estimate water flow rates, temperature profiles, and circulating rates from different geological models of the wells. Two of the wells, GB-1 and ES-1, are not expected to penetrate enough high permeability sandstone to support the minimum water flow rates of 5 l/s and so are ruled out as viable aquifer producers.

GB-2 is a deviated well that penetrates the Kinnesswood and Knox Pulpit formations, the best quality regional aquifers, in a zone where the fault may enhance the permeability even more, and has potential to supply 5 to 20 l/s of water at a surface temperature of 25 °C (± 2 °C). Such a well will be produced using an electric submersible pump which will require 20 - 40 kw of power to deliver 15 l/s of flow (although the volumetric rate will vary with the rock quality).

GB-2 is taken forward and drilling designs are provided with three outcomes: 1) a dry hole scenario; 2) a 5 l/s scenario; and, 3) a 15 l/s scenario.

The vertical wells have been modelled as heat pump circulating wells, and therefore would not produce any aquifer water at the surface. Only deeper wells, up to 2500 m, have the potential to give surface temperature increase of 5 ^{o}C at reasonable circulation rates (e.g. 8 l/s). A deep GB-1 well as a heat pump could be taken forward in Phase 2 as an alternative heat source.

The proposed GB-2 deviated well can be drilled across the fault from the Guardbridge site to a depth of 1200 m. A casing string set will isolate the shallow geology and a slotted liner used to prevent hole collapse of the target intervals. Such a well will require a 100 tonne conventional drilling rig and well control, logging and coring tools will assess the aquifer quality. In the most likely case, the drilling phase will take 24 days, including rig mobilisation and demobilisation. If coring and logging demonstrate that the well will not flow adequately, then the well will be suspended. Low cost options have been investigated that would allow exploratory wells to be drilled and this could result in the recovery of regionally significant data on the performance of the aquifers at depth, although none of the boreholes could be completed to production stage due the drilling technology employed.

The drilling scenarios investigated do not include a re-injection well, in order to create an economically viable district heating network project, even though very preliminary hydrogeological modelling demonstrates that re-injection is required if the geothermal well is to be sustainable over 30+ years. Alternative management of produced water investigated in this report are: water disposal-to-sea and partial-full water recycling and re-use on site. The first option could have environmental consequences on the adjacent Eden Estuary, which is part of the Tay River and Eden Estuary Special Protection Area, and these potential impacts would need formal assessment by a competent authority (Fife Council and SNH) as part of a Habitat Regulations Appraisal, and an Environmental Impact Assessment is most likely required. The second option reduces the environmental impacts on the estuary, but has additional CAPEX and OPEX costs which are estimated. The opportunity to be innovative about partial water recycling and re-sale should be investigated in Phase 2.

The heat demand is based on preliminary district heating network layouts at different scales, based on the demand analysis. Demand has been assessed at

Guardbridge and the nearby towns of Leuchars and Balmullo, using the Scotland Heat Map and future development data provided by the University of St Andrews and the Fife Development Plan. These various options provide an indication of the potential annual and peak heating demands that can then be compared against the geothermal heating potential, and an economic modelling tool was developed to analyse the performance of the overall system, including key performance indicators to evaluate the financial viability. This analysis leads to a preliminary network design and an economic model of the potential scheme.

The District Heating Opportunity Assessment Tool (DHOAT) designed for the Danish Energy Agency analyses the Heat Map data and preliminary network designs and provides peak and annual demands and key performance indicators, namely total heat demand and indicative CAPEX, OPEX, REPEX and heat sales. All input parameters are modelled with an uncertainty of ±10%. Based on this analysis, the proposed development of one well and estimated heat supply is not sufficient capacity to provide heat outside of the Guardbridge site itself. All district heating network designs and economic models were therefore based on the aggregated customer base of the Guardbridge site. The economic model assumes that geothermal heat can supply 50% of the Guardbridge site needs (2,867 MWh/a), with a capacity of 0.42 MW, and the other 50% would be provided by the biomass plant. Revenues from heat sales are based on a heat sale price scaling (MWh and p/kWh) and costs of heat from the biomass plant.

An Excel model calculates the profitability of the scheme based on a CAPEX of £530,000 for the heating network and £1,517,000 for the well completion, flow tests and water treatment. OPEX and REPEX costs are principally power consumption for the heat and distribution pumps (£280,000), and a ESP and heat pump replacement after 10 years (£250,000). NPV and IRR are used to demonstrate viability for potential investors over a 21-year period; the best case scenario shows that the scheme might achieve a 10% IRR and a positive NPV. However, the heat sale price is too low to create sufficient margin to make the economic performance attractive. This is principally due to the cost of the geothermal heat. The capital cost of the geothermal well is a significant portion of the project CAPEX and does not vary with the well heat potential, which is a relatively modest value given the temperature and flow rate estimates presented. Flow rate is highly uncertain, while temperature is better constrained and low due to the shallow depth of the proposed well. The district heating network requires higher temperatures and the addition of a heat pump increases the capital costs and adds a relatively high operating cost for the electricity to run the pump.

The carbon emissions reductions are compared to an individual gas boiler alternative (business as usual [BAU]) and the geothermal-biomass heat network shows an 84% reduction in carbon emissions, assuming that the biomass boilers and geothermal heat pumps each supply 50% of the network demand. About 58% of the emissions reduction (13,878 tonnes CO_2/kWh relative to BAU) is attributed to heat generation from the biomass plant and the remaining 42% (9,812 tonnes CO_2/kWh relative to BAU) is attributed to the geothermal well and the heat pump. These figures are based on a model lifetime of 20 years. The value of this carbon saving has not been included in the economic model, however it could be considered to represent an additional savings compared to the business-as-usual alternative.

The heating network can be enhanced at a subsequent stage to provide combined heating and cooling for the site. This would increase the utilisation of the heat pump by operating in combined heating and cooling mode during inter-seasonal periods. Although not explored in any extensive technical or economic sense, the system could also potentially be used to fill separate hot and cold seasonal heat stores.

Requirements for Phase 2 would begin with a non-invasive geophysical survey to provide imaging of the fault and the target aquifers in the subsurface. This could be completed in three months. Phase 2 would most likely require the preparation of an Environmental Statement before any drilling could commence on site, particularly addressing the viability of disposal of water to the sea. However, current developments at Guardbridge have required Environmental Statements (i.e. since 2014) and much baseline data already exists. The time required to complete an EIA range from 12 weeks to prepare the report, or up to one year of time if SNH and Fife Council require additional new data. A benefit of the Guardbridge site is therefore its status as an industrial site with a pre-existing history in terms of Environmental Statements. Ideally, Phase 2 would culminate in revised well designs, procurement of the drilling rig, and test drilling to intercept the fault and target aquifers. The time and costs are estimated and depend on the choice of drilling option. A positive outcome from a test borehole would lead to the design of a full production well and progression of the project as a Technology Demonstrator. Regardless of whether the test borehole proves that the

Guardbridge District Heating Network project is viable, the data recovered as part of the test drilling (core samples, flow tests and water chemistry) will be highly significant for de-risking hot sedimentary aquifer exploration across central Scotland.

The economic feasibility of the Guardbridge geothermal heat project is dependent on the best case scenario for flow rates, along with a large number of other poorly constrained variables. It could be economic, but there is a very large uncertainty in the geothermal heat estimates. However, the additional value in the potential research that can be achieved at Guardbridge in de-risking hot sedimentary aquifer exploration in the Central Belt of Scotland, as well as integrating low carbon heat source exploration with other technologies, including dual heating and cooling and water recycling, should be considered when deciding to progress this project.

ACKNOWLEDGEMENTS

Several people contributed to the analyses within this report but are not named as authors. Dr Rachael Ellen of the British Geological Survey supported the development of the geological model in Midland Valley's Move software, and Lucy McKay and Sarah Alexander, students at the University of St Andrews, contributed significantly to the geological modelling (McKay) and hydrogeological modelling (Alexander). Carolyn Bell of Resource Efficient Solutions is thanked for her contribution to project management.

The authors acknowledge the use of the Move Software Suite granted by Midland Valley's Academic Software Initiative to the University of St Andrews and FEFLOW® (licensed to the British Geological Survey).

CONTENTS

1. INTRODUCTION

1.1 Project Scope

This feasibility study investigates whether a geothermal district heating system, which accesses Hot Sedimentary Aquifer (HSA) resources underlying a brownfield site at Guardbridge in northeast Fife (Fig. 1.1), can be developed in a cost-effective manner. The Guardbridge site is located in some of the highest productivity aquifers in Scotland (Fig. 1.2), based on recent groundwater productivity assessments and the AECOM report into deep geothermal energy potential in Scotland (Gillepie et al., 2013). This project's scope is to assess the available geological information and estimate the Hot Sedimentary Aquifer (HSA) heat supply, calculate the current heat demand at the Guardbridge site, Guardbridge village, and the nearby towns of Leuchars and Balmullo, and incorporate future Guardbridge development plans (provided by the University of St Andrews) and anticipated growth in housing stock (from Fife Council) to estimate future heat demand. The capital, maintenance and repair costs for the geothermal well and designed district heating network are used to develop economic models for a number of district heat network scenarios. A key aspect of this study is an

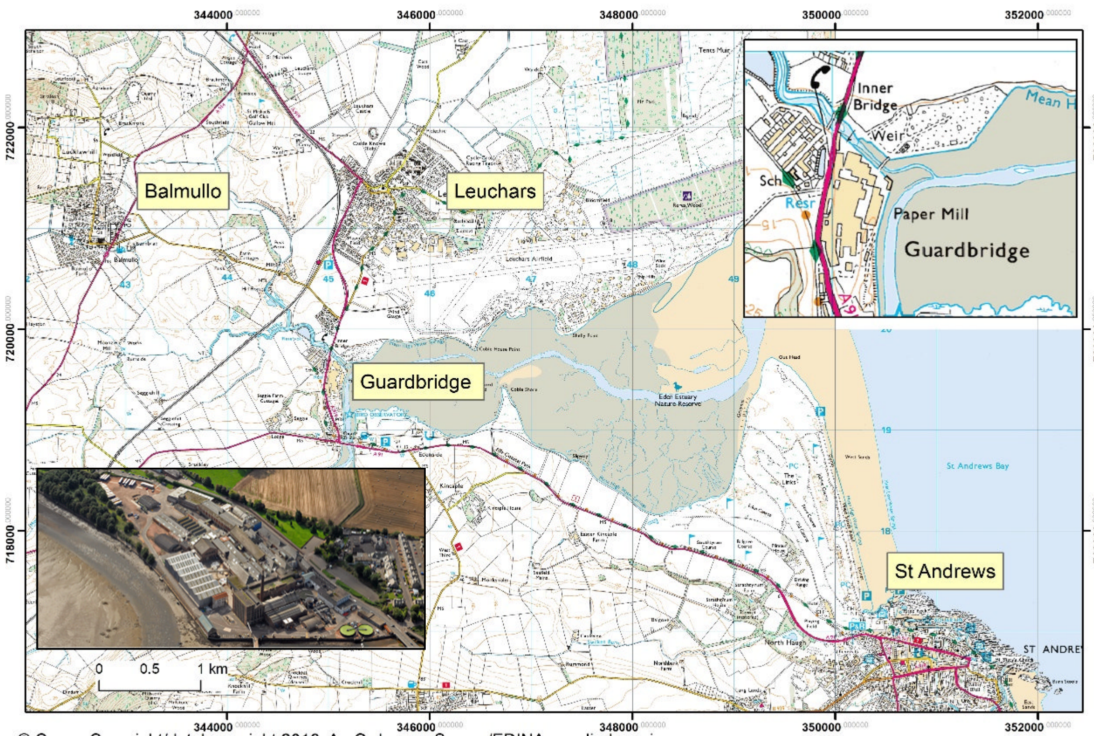


Fig. 1.1. Location of Guardbridge site in relation to surrounding communities. Inset map (top right) shows Guardbridge site in more detail. View in aerial photo (bottom left) is towards the southwest.

evaluation of the opportunities to cost effectively de-risk deep geothermal exploration in Central Scotland, and to outline the potential for developing geological heat storage systems. The study identifies the key legislative and environmental issues, risks and uncertainties associated with any exploration and production, involves stakeholder engagement, and makes recommendations for a Phase 2 stage for geothermal heat development at Guardbridge.

The old Guardbridge paper mill is owned by the University of St Andrews and is currently being transformed into a major low-carbon energy innovation centre. An investment of £25m was awarded to install a 6.5MW biomass heating centre at

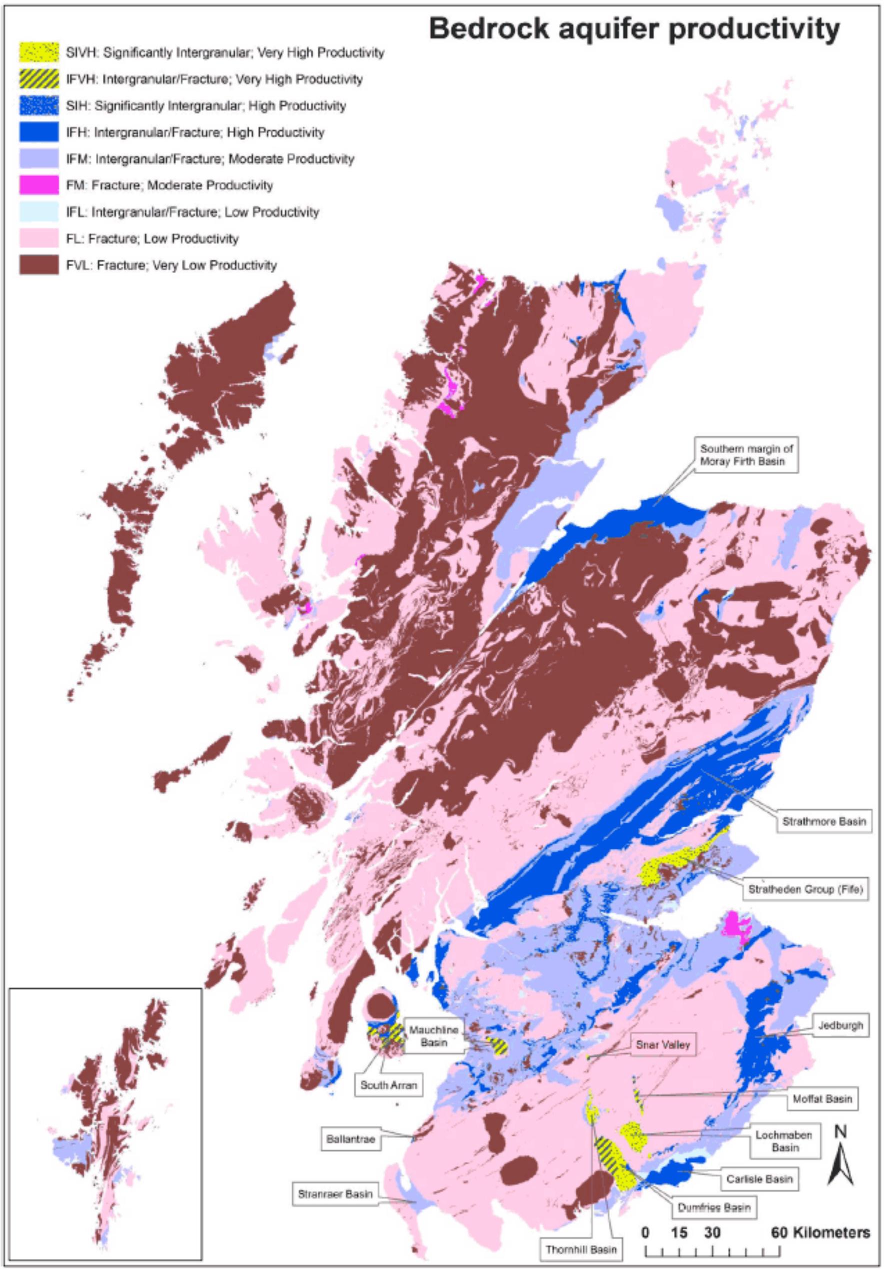


Fig. 1.2 Bedrock productivity map based on rock characteristics and type of groundwater flow. The map does not account for variability in productivity with depth (from Ó`Dochartaigh et al., 2011).

Guardbridge, and develop a district heating scheme for a subset of the University buildings in St Andrews; this will be operational during 2016. The new remit for Guardbridge as a low-carbon energy innovation centre, which will support research and development into energy integration, end- or off-grid supplies and circular economies, provides a very suitable location for exploring the potential for a geothermal heating scheme to serve the buildings and businesses within the Guardbridge site, and district heating networks for the communities in close proximity to the site.

1.2 Objectives

The key challenges and outstanding questions limiting the commercial development of geothermal heat energy in Scotland are:

- establishing the economic feasibility of geothermal exploration for heat;
- the lack of adequate datasets that reduce the risks associated with expensive drilling projects,
- the need for more sophisticated optimisation techniques accommodating well design, heat pump usage, and exploration depth,
- the lack of sub-surface geological and fluid flow models which provide frameworks for identifying and developing reservoirs that can sustain long term fluid and heat flow, and
- the development of diverse energy storage systems, and integration of geothermal storage into existing energy production and storage methods.

To test the old assumptions that geothermal resources are not economic, two of the key outputs from this feasibility study will be the economic model and business case based on different heat demand options, and an optimised model of well design based on different exploration strategies. Both are transferable to similar operations at other geothermal sites. The key objectives are therefore to:

- design a geothermal well that will be drilled in Phase 2 of the project, and secure valuable information on the Fife regional sub-surface geology and geothermal properties of the primary aquifer,
- explore how advanced drilling techniques, such as directional drilling, can be deployed to improve geothermal recovery,
- demonstrate how a geothermal system can integrate with an existing biomass heating installation to optimise both schemes and provide a district heat network for on-site industries and the local community,
- evaluate the potential for storage of seasonal heat energy in the subsurface (a first in Scotland), and
- assess the relative merits of water treatment and on-site recycling, re-injection or disposal to sea.

2. METHODOLOGY

2.1 Overview of methods

In the following sections of this report, each of the key components of our feasibility study are presented. The 3D geological model and rock characteristics are presented first and form the baseline data for the geothermal well design. Different well options are investigated based on the underlying geology, the rock characteristics, and estimated flow rates and water temperatures. The well performance scenarios are integrated into a district heating network design, and an economic model has been constructed that includes the heat demands for current and future scenarios and the capital, operation and maintenance costs of exploration, production and heat network development. Finally, the legislative and environmental issues arising from any HSA geothermal heat project are investigated with input from the relevant regulatory bodies, and recommendations for Phase 2 of the project to develop on-site heat and storage systems at the Guardbridge site are presented.

2.1.1 ***Geological models***

A regional-scale 3D geological model was developed by the University of St Andrews and the British Geological Survey using the 1:100,000 – 1:250,000 British Geological Survey digital maps, geological data from all the surrounding boreholes, and previously constructed geological cross-sections. One aspect of the geological modelling involved choosing an orientation for the Dura Den Fault which is located to the south of the Guardbridge site, and modelling the amount of offset and horizontal extent of the fault zone. This involved incorporating previous published work, including a PhD thesis. All data was compiled in Midland Valley Move™ software and the depths to the relevant sedimentary units, their orientation and thickness, and the behaviour of the Dura Den Fault are presented as a number of cross-sections (Section 3.1).

Simple 2D and 3D hydrogeological models have been constructed which incorporate rock characteristics described below and test flow rate scenarios for the sedimentary aquifers (Section 3.4). The modelling is limited by the lack of necessary data, namely adequate detail on the geological units, aquifer recharge, source of water, and influence of the saline wedge from the Eden Estuary. The modelling is performed in FEFLOW®, a finite element fluid flow model and was performed by the British Geological Survey and the University of St Andrews.

2.1.2 ***Geothermal well design and regional impacts***

The geological model provides estimates of the thicknesses and depths of the sedimentary units for both sides of the Dura Den Fault. In order to characterise the sedimentary rock characteristics for the units, such as porosity and permeability, a combination of wireline datasets from onshore oil and gas wells, and published hydrogeological data, were used (compiled by Town Rock Energy Ltd and the University of St Andrews). The necessary and sufficient data do not as yet exist for the sedimentary aquifers below Guardbridge, and this is one of the limiting aspects of this (and any) geothermal study. However, the wireline data is representative of rocks with similar properties and provides estimates for the rock characteristics at depths relevant to this study (up to 2500 m depth).

Each sedimentary unit is given a porosity, permeability and thickness, with appropriate levels of uncertainty (Section 3.3). The final aspect of the geological investigation is to define the change in temperature with depth, called the geothermal gradient. The study updates the geothermal gradient of Gillespie et al. (2013) to calculate temperatures at depth.

Well design was undertaken by Town Rock Energy Ltd and utilises the geological model, rock characteristics and geothermal gradient estimates. Four well scenarios were proposed (two on the Guardbridge site and one off-site) and different pumping technologies were investigated. Well performance is estimated based on a range of possible flow rates and water temperatures at the surface, and costs associated with drilling and production are calculated (Section 3.3).

A regional approach to de-risking geothermal exploration has been developed by Town Rock Energy Ltd which utilises an approach standard in the oil and gas industry (Section 3.5), and is generally applicable to the Central Belt of Scotland. The regional impact of the well design results are outlined in Section 3.6.

The well design and drilling strategies were fully costed to well production stage (Section 4). Based on the initial productivity predictions, it was possible to eliminate three of the well scenarios and focus the final economic model on one well scenario.

2.1.3 ***District heating network design and economic model***

The aim of this part of the study was to prepare preliminary district heating network layouts at different scales, based on the demand analysis and the Scottish Heat Map (www.gov.scot/heatmap), and was conducted by Ramboll Energy (Sections 5 - 6). The various options provide an indication of the potential annual and peak heating demands that can then be compared against the geothermal heat potential estimated for the geothermal well design. An economic modelling tool was developed to analyse the performance of the overall system, to incorporate all costs associated with the network construction, operational costs of the well on completion, and includes key performance indicators to evaluate the financial viability (Sections 7 - 0).

2.1.4 ***Environmental impacts and regulatory requirements***

The Guardbridge site is adjacent to the nationally important Eden Estuary, which is a Site of Scientific Interest and a Local Nature reserve. It is also part of the Firth of Tay and Eden Estuary Special Area of Conservation. Gavin Johnson (Operations Officer for Fife SNH) has been made aware of the project and provided an outline of the issues and regulatory requirements. An existing set of Environmental Statements, approved by Fife Council in 2014, document the identified impacts on air quality, noise levels, water resources, landscape, ecology and nature conservation arising from the ongoing construction and development at Guardbridge and these were reviewed for this report, along with the Regulatory Guidance:Geothermal Heat in Scotland publication by DECC (2016). Guidance was also sought from SEPA (Steve Archibald, Glenrothes office) on abstraction and disposal regulations and the Water Environment (Controlled Activities) Regulations (2011) was reviewed to outline the levels of authorisation that will be required.

2.1.5 ***Stakeholder Engagement***

The University has been involved with community engagement over a protracted period of years due to the developments at the former Guardbridge Paper Mill. This communication has increased over the last 12 months due to acceleration of on-site demolition and construction, and the closure of sections of the road between the site and St Andrews as the pipes connecting the biomass plant to St Andrews are Leuchars and the A91 are put in place. The University has incuded discussions about the potential for a geothermal well into these discussions, involving Councillor Brett and members of the Community Council.

2.2 Role of consortia partners

The University of St Andrews was Lead Partner in this feasibility study. The British Geological Survey and the University of St Andrews developed all the geological and hydrogeological models. Town Rock Energy Ltd, with the University of St Andrews, developed all the well *Statement of Requirements* and Town Rock Energy developed the well options and drilling strategies, and the costings associated with well exploration, production, operation and maintenance. Ramboll Energy evaluated the heat demand, designed the district heat network and built an economic model for the project. Resource Efficient Solutions had responsibility for project management, and the University of St Andrews, with Iain Todd Consulting, coordinated the stakeholder engagement. The University of St Andrews investigated the legislative and environmental issues and had responsbility for the compilation of the final report.

2.3 Data sources and key documents

Datasets	Sources
Ordnance Survey Maps	Digimap through Academic License with EDINA. 1:10,000 Scale Colour Raster [GeoTIFF geospatial data], Scale 1:10,000, Tile(s): no41ne; no41nw; no42se; no42sw; no51nw; no52nw. Updated: March 2013, Ordnance Survey, Using: EDINA Digimap Ordnance Survey Service, http://digimap.edina.ac.uk, Downloaded: March 2013.
Digital Terrain Models	Digimap through Academic License with EDINA. OS Terrain 5 DTM [ASC geospatial data], Scale 1:10,000, Tile(s): no41ne; no41nw; no42se; no42sw; no51nw; no52nw. Updated: March 2015, Ordnance Survey, Using: EDINA Digimap Ordnance Survey Service, http://edina.ac.uk/digimap, Downloaded: June 2015
British Geological Survey digital maps and cross-sections	1:100,000 to 1:250,000 NO41 and NO49 tiles. Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved.
Scottish Natural Heritage shapefiles for protected areas	Public sector information licensed under the Open Government Licence v3.0.
Wireline data	Inch of Ferryton #1; Firth of Forth #1; Milton of Balgonie #1, #2, #3; Thornton #1; Cousland #6; Carrington #1; Midlothian #1; Stewart #1; Data analysed by Town Rock Energy and underlying analyses are not presented here.
Heat map demand	Scotland Heat Map http://www.gov.scot/heatmap Local Development Plan http://www.fifedirect.org.uk/fifeplan FIFEplan Fife Local Development Plan Proposed Plan Pre-examination Editing – June 2015) Guardbridge Energy Centre Master Plan (revised January 2016) and input from Guardbridge Director (Ian McGrath)

Key Documents

Regulatory Guidance: Geothermal Heat in Scotland (2016)

Scottish Government (DECC) *http://www.gov.scot/Topics/Business-Industry/Energy/Energy-sources/19185/GeothermalEnergy/RegulatoryGuidance*

AECOM (2014) Study into the Potential for Deep Geothermal Energy in Scotland: Volume 1 & 2

Volume 1 http://www.gov.scot/Resource/0043/00437977.pdf
Volume 2 http://www.gov.scot/Resource/0043/00437996.pdf

Supporting Guidance (WAT-SG-62) Groundwater Abstractions – Geothermal Energy

https://www.sepa.org.uk/media/143949/watsg62_groundwater_abstractions_geothermal_energy.pdf

The Water Environment (Controlled Activities) Scotland) Regulations 2011 (as amended)
http://www.sepa.org.uk/regulations/water/

Conservation (Natural Habitats, &c.) Regulations 1994, as amended – guidance
http://www.snh.gov.uk/protecting-scotlands-nature/protected-areas/international-designations/natura-sites/

Natura sites and the Habitats Regulations - How to consider proposals affecting Special Areas of Conservation and Special Protection Areas in Scotland
http://www.snh.gov.uk/publications-data-and-research/publications/search-the-catalogue/publication-detail/?id=1364

2.4 Assumptions and limitations

The conclusions and recommendations arising from this report are based on assumptions outlined below and are limited by the considerable uncertainty regarding the quality of the geothermal resource. All estimates assume that the HSA behaves in a similar way to rock intervals that are within the eastern Midland Valley and have been analysed using wireline data; those rocks have been drilled at depths similar to the position of the aquifers beneath Guardbridge. The behaviour of the fault adjacent to the site is critical and could either be a conduit or an inhibitor of flow. These aspects of rock characteristics and potential flow rates, which control the geothermal heat potential, are the largest unknowns in this study. Temperature at depth is also not tightly constrained, but since geothermal gradients for the onshore sub-surface are known from bottom hole temperatures, the uncertainty on this is smaller (± 3-4 °C /km). It is impossible to constrain these parameters better without drilling to reasonable depths (500 - 1000 m).

The Scotland Heat Map has been used to calculate heat demand, and most of the uncertainties in these estimates arise from the scale of future expansion of the network within the towns around Guardbridge and within the site itself. If new housing projects are of a larger scale than modelled in this report, our residential heat demand estimates are too low. The data used to finalise the heat demand estimates for the Guardbridge Energy Centre are based on an up-to-date version of the Guardbridge Energy Centre master plans (revised January 2016).

The economic viability is based on heat sale price and and biomass heat sale cost, and it is possible that these will change. All price estimates for CAPEX, OPEX and REPEX are subject to inflation and although inflation of costs has been accounted for in the network development costings, prices quoted from December 2015 to January 2016 may be subject to change as the project develops.

3. GEOTHERMAL MODEL DEVELOPMENT

3.1 Geological model

A regional-scale geological model (1:100,000 – 1:250,000) was constructed by compiling the surface geology maps with 1) a digital surface terrain model (tiles NO41 and NO49), 2) projected faults and rock formation boundaries (horizons), 3) coded and georectified boreholes displaying the top of each formation, 4) modelled faults to a depth of 1000 m with an average plunge of 60°, and 5) georectified dip data and the 1:50,000 DiGMapGB cross sections for the British Geological Survey Sheets 41 (North Berwick) and 49 (Arbroath). For simplicity in this regional-scale model, faults with a throw <30 m and intrusions <500 m in diameter were excluded from the model.

3.1.1 ***Background geology***

Based on cross section interpretation, the regional geology consists of strata dipping towards the SE. To the north of Guardbridge lies the thick Ochil Volcanic Formation (approximately 2000 m thick) consisting of olivine basaltic lavas and volcaniclastic rocks, offset by a series of normal faults with an average displacement of 200 m. The top of the lavas and associated volcaniclastic rocks of the Ochil Volcanic Formation are overlain by sandstones of the Scone Sandstone Formation which display an average thickness of 300 m. The Scone Sandstone Formation consists of purple-brown and purple-grey, fine- to coarse-grained, commonly cross-bedded sandstones with subsidiary siltstone, mudstone, conglomerate, sparse andesitic lava flows and some calcareous beds with concretionary limestones towards the top (Armstrong et al., 1985; Browne et al., 2002).

Overlying the Scone Sandstone Formation is the Upper Devonian Glenvale Sandstone Formation with gradational contacts consisting of brown, red, purple, yellow and cream feldspathic sandstones, commonly containing bands of red siltstone and pebbles of silty mudstone, but no siliceous pebbles (Browne et al., 2002). Honouring all available geological data, the cross sections display the Glenvale Sandstone Formation as having an average thickness of 600 m. Beneath Guardbridge, the top of the Scone Sandstone Formation is located at ~530 m. Although not exposed at the surface in northeastern Fife around Guardbridge, the highly and moderately productive Upper Devonian Knox Pulpit and Kinnesswood formations, respectively, sit stratigraphically above the Glenvale Sandstone Formation, and are assumed to be present in the subsurface around Guardbridge.

Their type locality is in Glen Burn near Kinnesswood and Loch Leven (Browne et al., 2002). The highly folded and faulted rocks of the Inverclyde and Strathclyde groups overlie the Upper Devonian sedimentary rocks in the area to the south of Guardbridge.

3.1.2 ***Model construction***

The Late Carboniferous Dura Den Fault with a normal sense of displacement (downthrown to the south) separates the Upper Devonian sedimentary and igneous rocks in the north from the Carboniferous sedimentary rocks in the south (Fig 3.1). The antithetic Maiden Rock Fault is downthrown to the north, and these two fault systems (Dura Den and Maiden Rock) form a graben-type structure. The Maiden Rock and Ceres faults form an en echelon (right stepping) structure such that the graben is rhomb-shaped in the vicinity of Guardbridge. Rocks in the hanging wall of the Dura Den and Maiden Rock faults have 'rollover' anticline and drag folds associated with them (not shown on Fig. 3.1).

The Dura Den Fault orientation drawn from all cross sections (6 sections in total and only two presented here) were collated in Move™ to produce the listric Dura Den Fault surface soling at a depth of ~6000 m (Fig. 3.2). The modelled Dura Den Fault is the best interpretation honouring all available geological data. The location and termination of the fault was determined from published British Geological Survey 1:50,000 surface data and no additional field evidence is included in this analysis as the exposure of the fault is very poor in northeast Fife. The actual

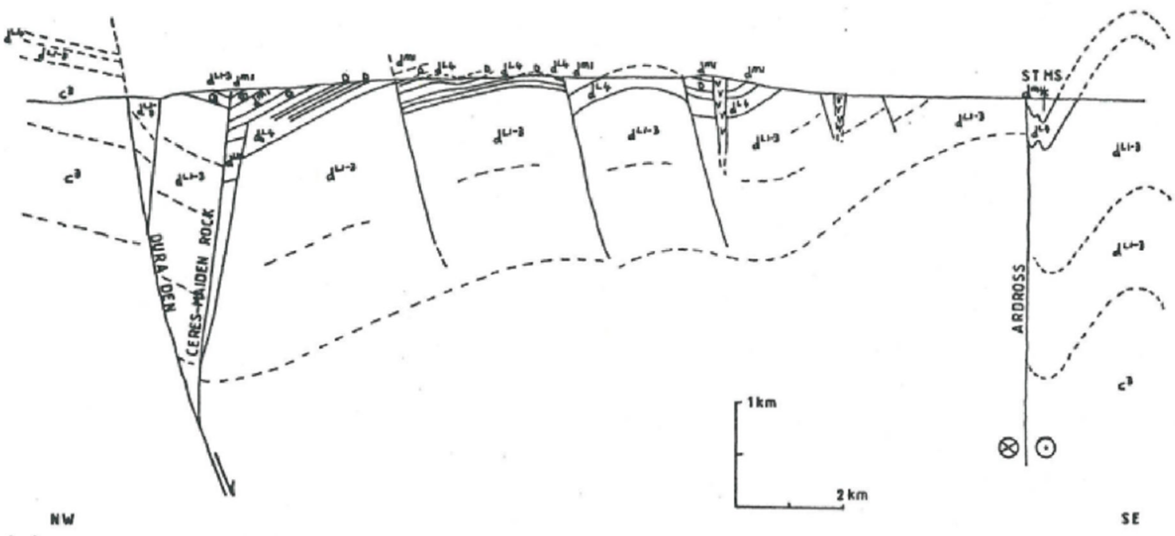


Fig. 3.1 Graphical representation of the Dura Den Fault (McCoss, 1987). The cross-section is schematic, combining geological observations from many sites to summarise the sub-surface geometries of all formations and faults. Abbreviations: c3 Upper Old Red Sandstone, dL1-3 Calciferous Sandstone Measures, dL4 Lower Limestone Group, STMS St Monance Syncline. Vertical exaggeration present.

location of the fault is not visible in the Guardbridge area, but the Guardbridge Paper Mill borehole (GR: 345010 719649) is within Upper Devonian rocks (Glenvale Sandstone Formation) and therefore the borehole lies north of the fault. The current model therefore depicts the whole of the Guardbridge site to be in the footwall of the Dura Den Fault, however, it is possible that the fault is further north within the southern end of the Guardbridge site (Fig. 1.1).

Offset on the Dura Den Fault at Guardbridge (Section 3; Fig. 3.2) is estimated at 723 m (within the error of cross section construction), however it is evident from the cross-section analysis that the Dura Den Fault displacement decreases towards the fault tip in the northeast, and increases towards the southeast. Displacements increase from about 236 m to 1615 m over approximately 10 km.

The proximity of the Guardbridge site to the Dura Den Fault is therefore significant because of the variability of the geology on either side of the fault (Fig. 3.1, 3.2). The southern side of this fault contains younger rock sequences and therefore there is the potential to access the highly productive Kinnesswood and Knox Pulpit formations. Additionally, productivity within the Dura Den Fault zone could be good because the fault will have a zone of damage which will influence the important rock characteristics, such as porosity and permeability.

A fault "damage" zone was produced around the Dura Den Fault based on calculations presented in Childs et al. (2009) and this permits a prediction of fault zone width based on the amount of fault displacement and the fault geometry. Fault displacement (in metres) was measured within *Move* and fault zone thickness incorporates the fault core, the zone of most intense deformation associated with faulting, as well as the damage zone of related fracturing and brecciation of rock adjacent to the fault core. The core of the Dura Den Fault may be positioned within the limits of the modelled fault zone (Fig. 3.3). The calculated values used to produce the fault zone fault zone widths are presented in Table 1.

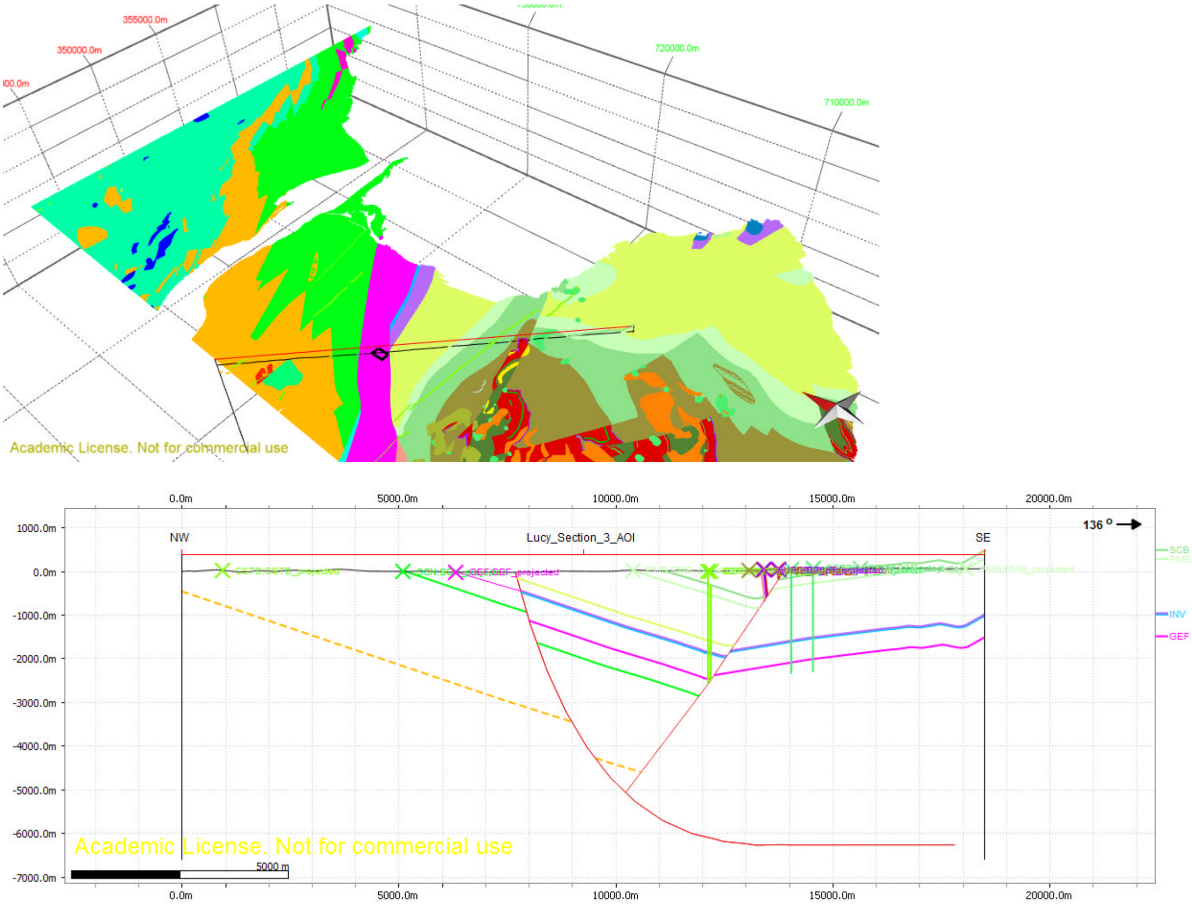


Fig. 3.2 Above: 1:50,000 Bedrock Polygon surface geology provided by the BGS. Guardbridge site represent by the black rectangle within the Glenvale Sandstone Formation (GEF), north of the Dura Den Fault. Below: Cross-section interpretation. Formations: orange dashed - Ochil Volcanics (OVF); green - Scone Formation (SCN); pink - Glenvale Sandstone Formation (GEF); blue - Inverclyde Group (INV); purple - Fife Ness Formation (FNB); yellow - Anstruther Formation (ARBS); light mint green - Pittenweem Formation (PMB); dark mint green - Sandy Craig Formation (SCB); olive green - Pathhead Formation (PDB); dark purple – Hurlet (Hur); red – Lower Limestone Formation (LLGS); bright green dashed - Central Scotland Late Carboniferous Tholeiitic Dyke Swarm (CSTD); green/blue intrusion - Scottish Late Carboniferous to Early Permian Plugs and Vents Suite (SCPPV).

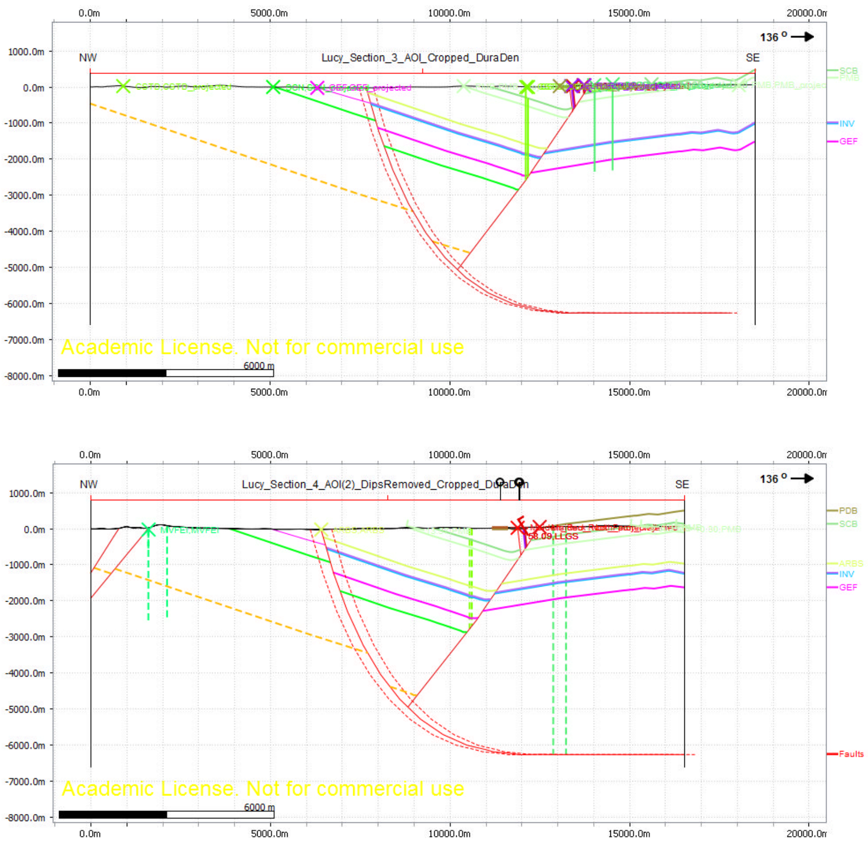


Fig. 3.3 Fault damage zone associated with the sections closest to Guardbridge (Sections 3 and 4). Boundary of the fault zone is represented by the dashed red lines.

3.1.3 *Production of simplified 3D geological model*

The final 3D Move model was created from the validated cross-sections and is presented as surfaces for the formations; these are either colour-coded horizons (the tops of formations) or faults. A 3D view of the model centred at Guardbridge and illustrating the fault zone displacement is presented in Fig. 3.4.

Table 3.1. Fault displacement and fault zone thickness. Sections 3 and 4 are presented in the text and the remaining sections are not presented as part of this report.

SECTION	DISPLACEMENT (metres)	FAULT ZONE THICKNESS (metres)
Section 1	235.9	20
Section 2	336.1	30
Section 3	**723.3**	**200**
Section 4	**810.8**	**300**
Section 5	1482.2	600
Section 6	1614.7	700

3.2 Limitations of the geological model

All interpretations behind the construction of the model are based on previously published maps and data, and relationships observed within Move™. The lack of data is the foremost limitation in producing a high-resolution model of the Carboniferous-Devonian subsurface geology. This includes insufficient detail about the position of formation (horizon) boundaries at depth, the lateral changes in formation thickness, and the location and geometry of the Dura Den Fault and other less significant structures. Borehole coding and interpretation was affected by the lack of data and some poor data quality in the existing borehole information. An average uncertainty for depths of horizons is estimated as ±10 m. Available borehole data is limited to total depths of 20 m to 241 m, and there are limited boreholes >100 m depth in the Guardbridge area. Unit thicknesses are based on available map evidence.

Subsurface structural complexity at depth is very difficult to model without more field, seismic and deep borehole data, and the orientation of rocks units and fault geometry at depth are necessarily simplified. Initially, all faults were assumed to display an average plunge of 60° with an extrusion depth of 1000 m, but the Dura Den and Maiden Rock faults were subsequently remodeled based on the interpetations of McCoss (1987), including the listric geometry of the Dura Den Fault. This structure was modelled in Move using the orientation of the hanging

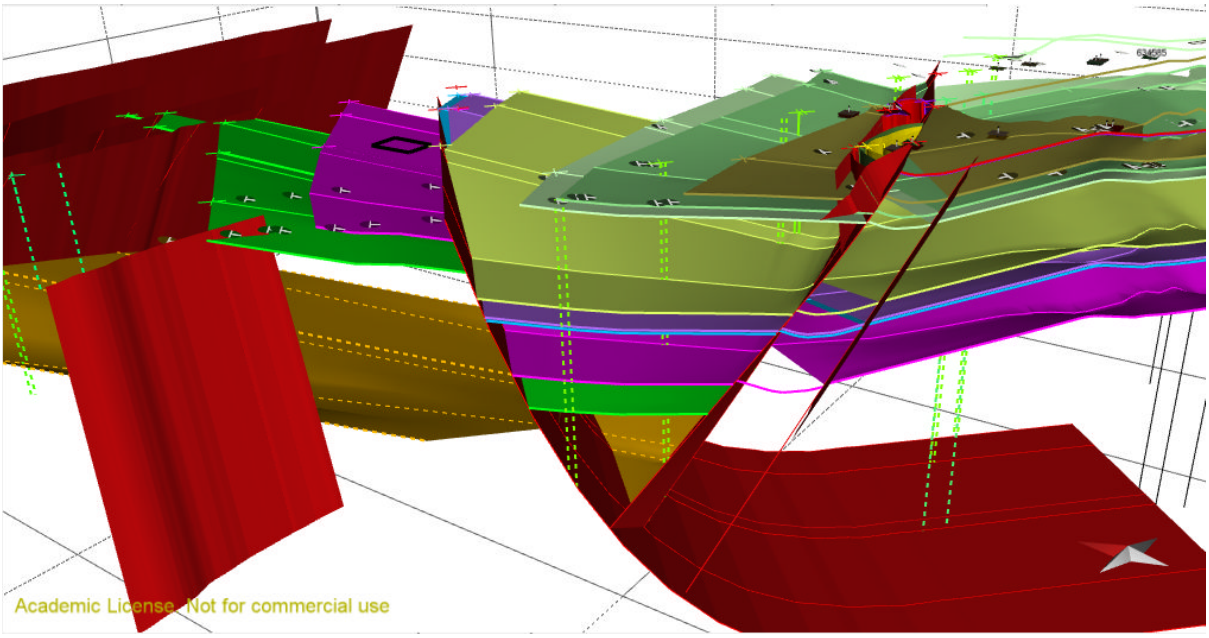


Fig. 3.4 3D view of the geological horizons (top of formations and fault surfaces) around the Guardbridge site looking northeast. Displacement of horizons (offset) on the Dura Den Fault is visualised and increases towards the southwest (out of the page). The target aquifer is between the purple and underlying green horizons.

wall horizons and the *Constant Heave* algorithm, which ultimately depends on accuracy of cross-section construction. Cross-section 4 was used as a proxy for fault construction. Other faults were modelled as planar structures at depth due to lack of available data, but in reality are most likely curviplanar horizons. No strike-slip component was taken into account during fault restorations (simple shear algorithm used), and no growth structure or damage structures are accounted for in the model.

3.3 Aquifer prospect evaluation

In order to investigate well design options, all the stratigraphic units and thicknesses were compiled, based on the available borehole data and the geological model presented in Section 3.1. As previously stated, the borehole penetration is no more than 241 m around the Guardbridge area and is ~100 m within the Guardbridge site, therefore depths and lithologies at deeper horizons are based on the extrapolation of the surface geology below Guardbridge and the existing cross-sections. All target horizon depths and thicknesses are based on the 2D and 3D regional geological model presented in the previous section and the closest and/or most detailed stratigraphy available (Browne et al., 1999; Browne et al., 2002; Shell, 2002; Walters et al., 2007; Dean et al., 2011). Permeabilities and porosities are estimated from published data of outcrop and shallow boreholes from Fife and the Midlothian areas (see sections 3.4 and 4.1).

This report presents four drilling scenarios for the Guardbridge Geothermal Energy Feasibility project. One on-site, relatively shallow, vertical borehole located on the footwall, and outside of the damage zone, of the Dura Den Fault. The first target is the **Scone Sandstone Formation**. The second drilling scenario is on the hanging wall of the Dura Den Fault in a location near the A91 and Edenside area; this well is also predicted to be outside the damage zone and to a depth of 1050 m. The target is the undivided **Kinnesswood** and **Knox Pulpit formations**. The third scenario is a deviated well starting at a second on-site location within the Guardbridge Energy Centre and deviating to a depth of 1100 m over 1000 m distance. The main target is the **Kinnesswood** and **Knox Pulpit formations** and the well will intercept the Dura Den Fault and damage zone for up to 400 m distance. The fourth scenario extends the previous well by drilling parallel to the dip of the **Kinnesswood** and **Knox Pulpit formations** to a depth of 1500 m over a total horizontal distance of about 2000 m.

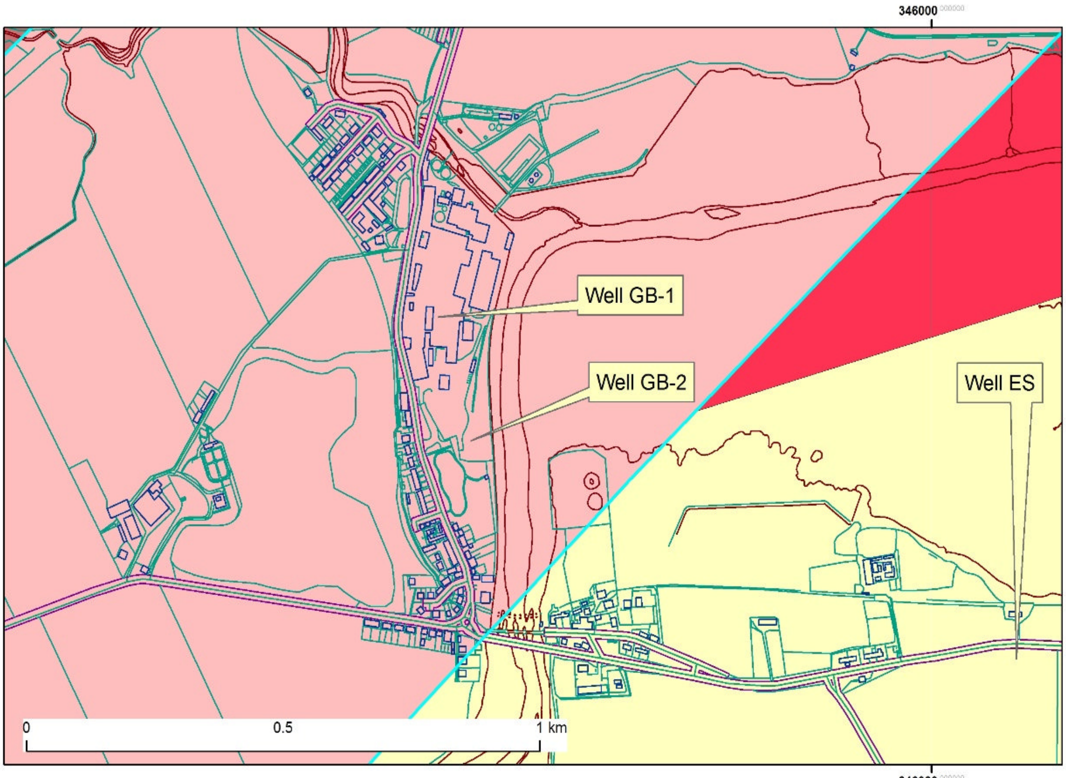


Fig. 3.5 Location of three wells for Guardbridge Geothermal Feasibility Project. Wells GB-1 and GB-2 are within the Guardbridge site and Well ES is located offsite. Basic geology shown for context: pink is the Upper Devonian Glenvale Sandstone Formation, and yellow and red are the Carboniferous Anstruther and Fife Ness Fms. The blueline is the estimated trace of the Dura Den normal fault.

3.3.1 *Scenario 1 - Well GB1*

The approximate location of the vertical well within the Guardbridge site (Well GB-1) is next to the proposed new Library building (345030 719460). Figure 3.5 shows the location of Well GB-1 within the site and its position relative to the road network and Eden Estuary. The site is easily accessible from the entry point to the site. Cross-section 3 and the 3D geological model (Figs. 3.2 and 3.6) illustrate the subsurface structure and the depths of the main horizons; Well GB-1 is on the footwall of the Dura Den Fault (Fig. 3.6), approximately 500 m northeast of the fault (though this structure does not outcrop near Guardbridge and its surface trace is not well constrained). The stratigraphic log for Well GB-1 (Fig. 3.7) is based on the intercepted horizons in cross-sections 3 and 4 (see Fig. 3.3) and the target horizon is chosen to maximise depth in suitably sandstone-rich successions of the

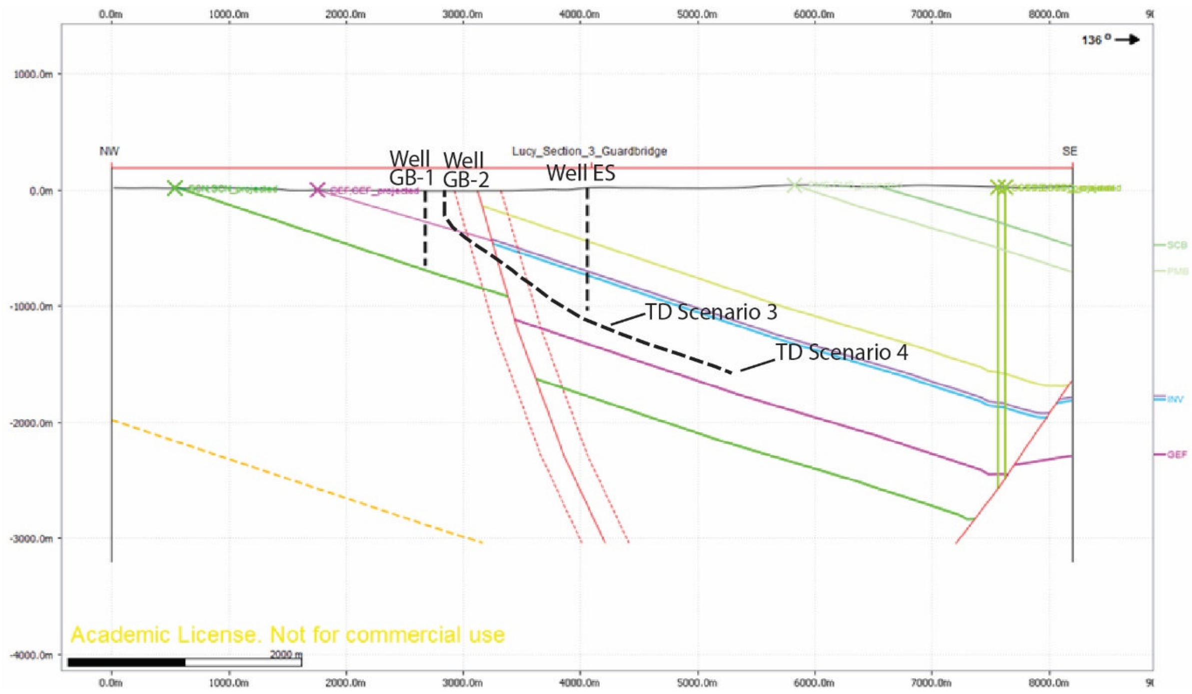


Fig. 3.6 Position of wells GB-1, GB-2 and ES relative to cross-section 3 (see Fig. 3.3-3.4). There are three well sites and one site (GB-2) has two total depth scenarios.

Scone Sandstone Formation, while avoiding the boundary with the Ochil Volcanic Formation. Further drilling beyond 700 m would penetrate into the Ochil Volcanic Formation and this unit continues to an estimated depth of 2500 m, though its stratigraphy is variable.

In modelling the 2D and 3D geological behaviour of the Guardbridge area, the fault orientation and damage zone have potential influence on the wells, and therefore the fault and damage zone have been modelled based on fault displacements of 723 metre and 810 metre for cross-sections 3 and 4, respectively (Fig. 3.3). The predictions for fault damage width in the 700 – 1000 metre depth range are 100 – 150 metre either side of the Dura Den Fault. The regional dip of the beds on the footwall and hanging wall are 15^{o} and 20^{o}, respectively, although the geometries and stratigraphy near the fault are not well constrained.

Scenario 1: Well GB-1
Coordinates: 345030 719460
Concerns:

- 12 m of boulder clay at top of sequence;
- shallow aquifer with 5 – 15 l/s potential flow rates in top 400+ m of Glenvale Sandstone Formation
- uncertain depth for boundary between Scone Sandstone Formation and Ochil Volcanic Formation
- potential for andesitic layers towards Scone-Ochil Volcanic Formation boundary (but well below main sedimentary target interval).

Uncertainties:

- exact position of the Dura Den Fault and the extent of the damage zone. Latter estimated to be 100 – 150 m either side of the fault, therefore well is likely to be outside of damage zone if fault is correctly positioned.

3.3.2 *Scenario 2 - Well ES*

The approximate location of the vertical well outside the Guardbridge site (Well ES) is next to the A91 in a local farmer's field. Figures 3.5 and 3.6 shows the location of Well ES and its position relative to road network, Guardbridge and Eden Estuary. The site is easily accessible from the A91. Section 3 (Fig. 3.2 – 3.3) illustrates the subsurface structure and the depth and thicknesses of the main horizons; Well ES is on the hangingwall of the Dura Den Fault, approximately 700 m southeast of the fault. The stratigraphic log for Well ES (Fig. 3.8) is based on the intercepted horizons in cross-sections 3 and 4 (Fig. 3.3) and the target is the Upper Devonian aquifer rocks of the Kinnesswood/Knox Pulpit formations. The modelled damage zone width is 100 - 150 metre either side of the fault and the regional dip of the beds on hanging wall are 20^{o} respectively, but geometries and stratigraphy near the fault are not well constrained.

Scenario 2: Well ES
Coordinates: 345770 718750
Concerns:

- ~6 m of unconsolidated sand and carse clay, with boulder clay at base;
- Anstruther Formation contains thin coals, plus organic-rich mudstones and siltstones which may contain oil (oil shales);
- Inverclyde Group rocks have thin evaporite and dolostone beds;
- Main target (Knox Pulpit Formation) has 5 – 15 l/s potential flow rates up to 400+ m depth, but uncertain at depths of 700 – 1250 m.

Uncertainties:

- exact position of the Dura Den Fault and the extent of the damage zone. Latter estimated to be 100 -150 m either side of the fault, therefore well is likely to be well outside of damage zone if fault is correctly positioned.

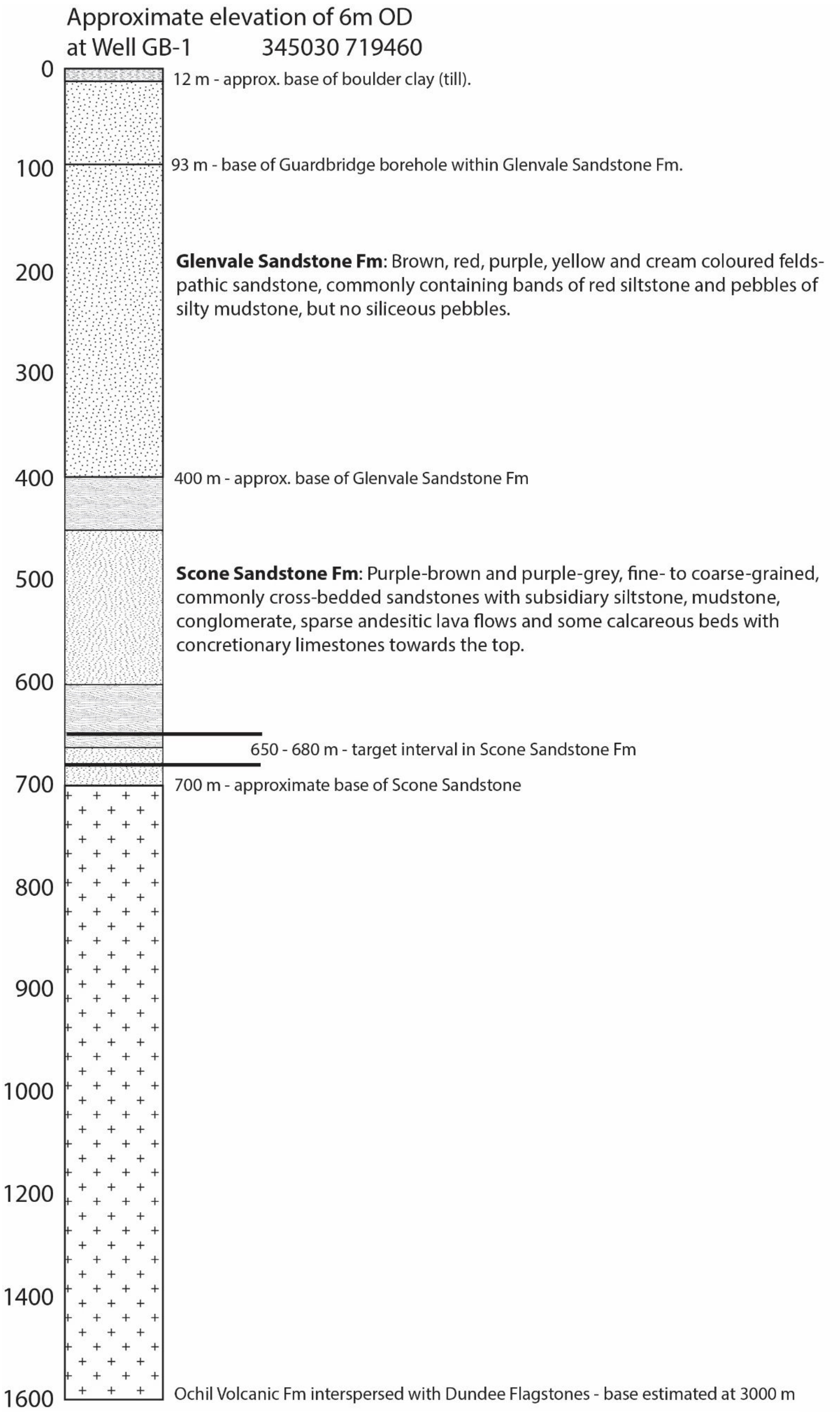


Fig. 3.7 Estimated stratigraphic log for Well GB-1 based on the 3D geological model and available stratigraphy.

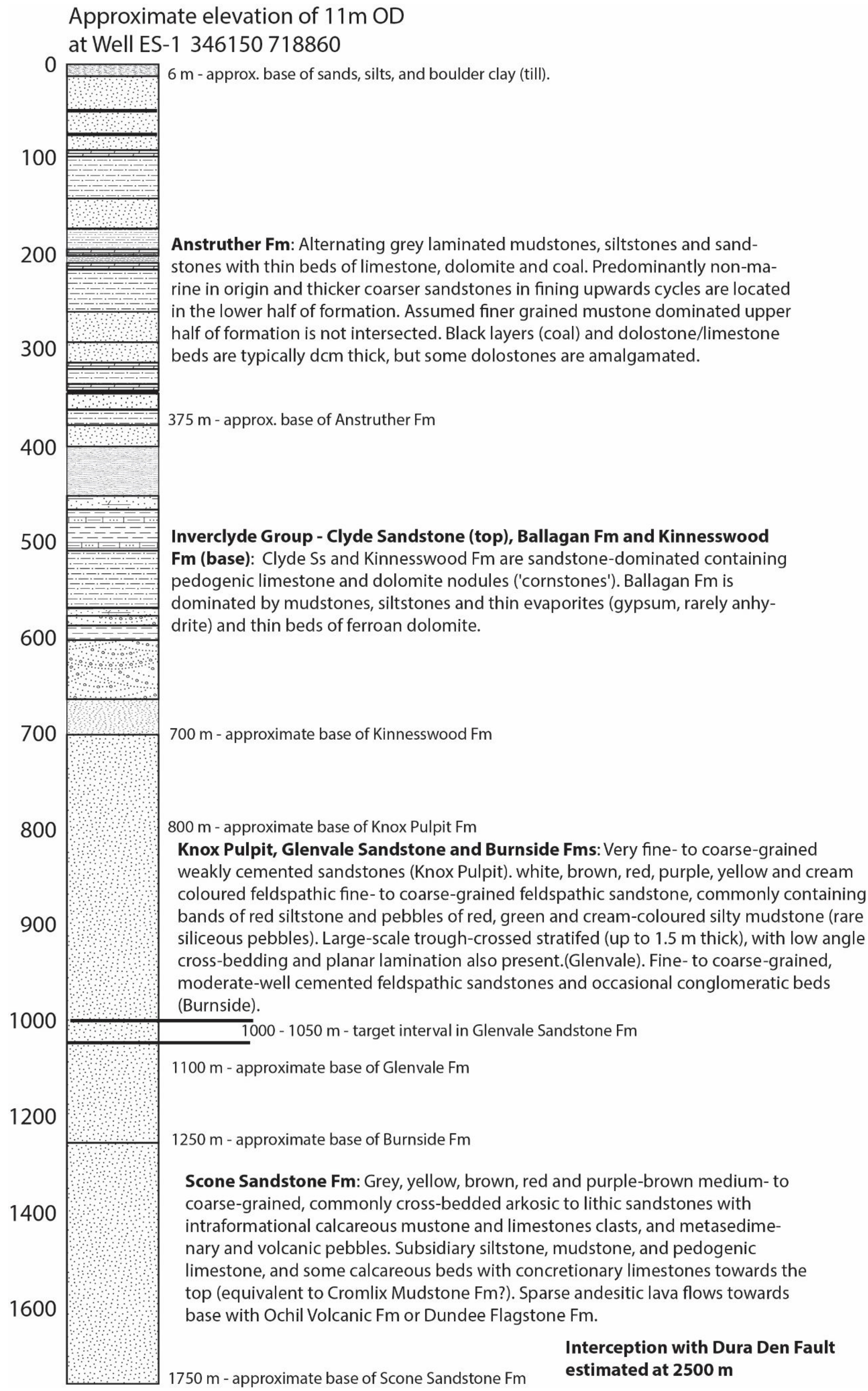


Fig. 3.8 Estimated stratigraphic log for Well ES based on the geological model and available stratigraphy.

3.3.3 ***Scenario 3 - Well GB2***

The approximate location of the top of the deviated well is within the Guardbridge site (Well GB-2 is 250 m south of Well GB-1). Figures 3.5 and 3.6 shows the location of Well GB-2 and its position relative to road network, Guardbridge and Eden Estuary. Cross-section 3 (Figs. 3.2 – 3.3) illustrates the subsurface structure and the depths and thicknesses of the main horizons; Well GB-2 starts on the footwall of the Dura Den Fault and at a depth of ~400 m begins to deviate through the fault zone and onto the hangingwall of the Dura Den Fault. The deviation requires the well to be parallel to a 20° dip, and at a depth of ~1100 m, over a horizontal distance of 1000 m. The total estimated drilling distance is 1325 m. Given the estimated width of the damage zone and angle of deviation as the well penetrates the fault and damage zone, about 460 m of drilling is estimated to be through this zone. The stratigraphic log for Well GB-2 (Fig. 3.9) is based on the intercepted horizons in cross-sections 3 and 4 (Fig. 3.3) and the target is the Upper Devonian aquifer rocks of **the Kinnesswood/Knox Pulpit Formation and Glenvale Sandstone Formation**. The modelled drilling distances were calculated using three punctuated drops in drilling angle (from vertical to 60°, 40°, and finally 20°).

Scenario 3: Well GB-2
Coordinates: 345110 719230
Concerns:

- 12 m of boulder clay at top of sequence;
- shallow aquifer with 5 – 15 l/s potential flow rates in top 400+ m of Glenvale Sandstone Formation on footwall; uncertain depth for boundary between Scone Sandstone Formation and Ochil Volcanic Formation on footwall; potential for andesitic layers towards Scone-Ochil Volcanic Formation boundary (but well below target interval);
- uncertain fracture network, cementation and mineralisation, and pressures across the damage zone and Dura Den Fault. Likely to intercept anticline and syncline structure in the Anstruther and Pittenweem formations.

Uncertainties:

- exact position of the Dura Den Fault and the extent of the damage zone. Latter estimated to be 100 – 150 m either side of the fault, but deviated drilling distance estimated at 460 m. Possible interception of multiple small faults and folds within the 460 m of drilling.

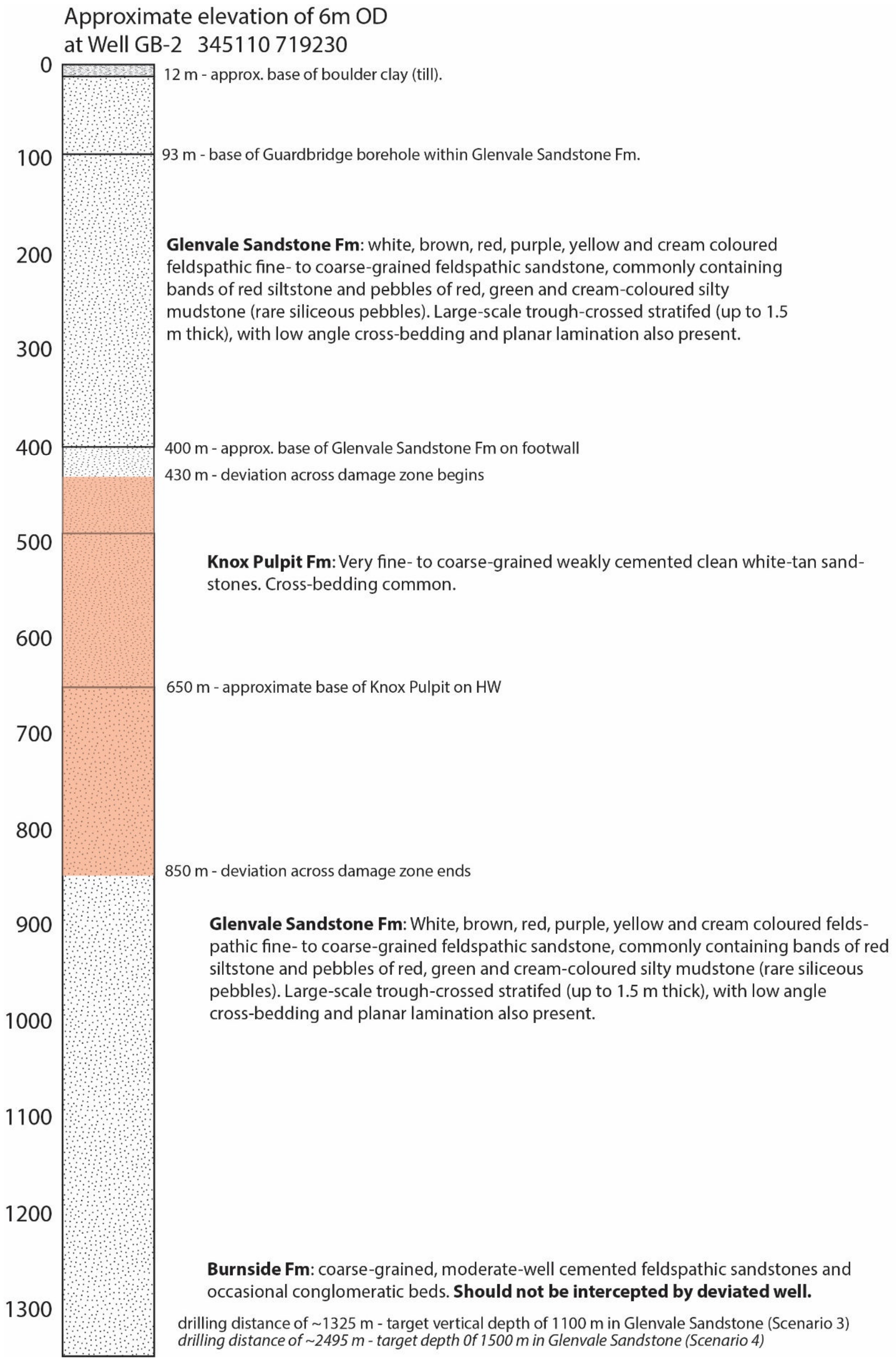


Fig. 3.9 Estimated stratigraphy for the deviated well (GB-2). Depth measurements are the drilled length of the deviated well and the pink interval represents the fault damage zone.

3.3.4 ***Scenario 4 - Well GB2***

The deviated well will be oriented parallel to dip (20°) at a vertical depth of ~1100 m and within the Glenvale Formation (Fig. 3.9). A continuation of the drilling at the same dip will permit the same geological unit to be targeted at a greater depth below the surface. An estimated drilling distance of 2495 m will target the Glenvale Sandstone Formation at ~1500 m below the surface.

Scenario 4: Well GB-2
Coordinates: 345110 719230
Concerns:

- Same concerns as scenario 3.

Uncertainties:

- Same uncertainties as scenario 3. Assumption that Glenvale Formation is of uniform thickness and that there are no further faults beyond the estimated damage zone.

3.4 Hydrogeological model

In order to estimate the groundwater flow rates and pathways for the HSA targets beneath Guardbridge, a review of the regional groundwaterflow system was undertaken. This provides a general overview of aquifer behaviour and the regional controls on sub-surface fluid flow. There are limitations to this analysis, however, because there is very little known about the deep sub-surface hydrogeology in Scotland, and therefore the geology beneath Guardbridge is insufficiently understood (i.e. aquifer thicknesses and porosity/permeabilities, behaviour of the Dura Den Fault); some of the key parameters required to model groundwater flow are unknown. The estimated hydrogeological properties are combined with the geological model developed in the previous sections to produce a conceptual and preliminary numerical groundwater flow model to test some necessary conditions for an economic HSA project at Guardbridge.

3.4.1 ***Regional groundwater flow system***

The north-western and south-eastern margins of the Midland Valley, marked by the Highland Boundary Fault and the Southern Upland Fault respectively, are elevated with respect to the lower lying Forth-Clyde Axis. Within the regional context, they present areas of highest fluid potential and could provide the driving force for recharge and downward flow to a deep circulating regional groundwater system. If recharge of cool water occurs north of the Ochill Hills (north of Guardbridge), deep-seated flow may occur from north to south beneath the volcanic rocks with corresponding upwelling and discharge along the Forth-Clyde axis and near the coastline (Browne et al., 1987).

In the Eden River Valley of northeast Fife, the groundwater flow system appears to be dominated by recharge from valley sides. The majority of the recharge is either discharged directly as baseflow to the river or displaces shallow groundwater which is later discharged as baseflow. Most flow is believed to be transported via shallow flow paths (Ó Dochartaigh et al., 1999) in the upper 100 m of aquifers, and most of these are weathered and fractured and have little intergranular permeability; a small component of the flow may be feeding into a deeper regional groundwater system.

The groundwater contour pattern within the Eden River valley implies that there are two components to groundwater flow: one perpendicular from the valley sides towards the River Eden and one parallel to the length of the valley. However, this longitudinal groundwater flow component down the valley towards the coast appears to be very small and is likely to be at depth, away from the influence of the near-surface regime and constrained by the geological complexity of the area and the reduced permeability of aquifers at depth. It is likely to be slow and in the direction of the general regional hydraulic gradient (Ó Dochartaigh et al., 1999).

Groundwater chemistry of the shallow groundwater of Fife and Strathmore provides no evidence for deep flow paths. The waters are weakly to moderately mineralised and are almost invariably oxygenated with detectable concentrations of dissolved oxygen (DO) and high Eh values (Ó Dochartaigh et al., 2006, Browne et al., 1987). There is no evidence from stable isotope and CFC analysis that these waters are especially old, though mixing between remnants of Pleistocene (more than 10,000 years old) waters and modern water has been proposed for other basins in Scotland (MacDonald et al., 2003) and cannot be wholly ruled out for Fife and Strathmore in the absence of radiocarbon data (Ó Dochartaigh et al., 2006).

Hence, evidence for deep groundwater circulation is, at best, inconclusive. Deep flows are probably small to moderate in volume, i.e. less than 10% of the total flow within the catchment, and limited to isolated discrete pathways along zones of tectonic weakness, such as faults (Browne et al., 1987).

3.4.2 ***Aquifer properties of the target formations***

As stated earlier, the Upper Devonian rocks of the Midland Valley represent some of the highest productivity aquifers in the Midland Valley and these are present under the Guardbridge site. The Upper Devonian Stratheden Group aquifer incorporates, in ascending succession, the Burnside, Glenvale, Knox Pulpit and

Kinnesswood formations and its base is marked by an unconformable contact with the Lower Devonian Scone Sandstone Formation (Arbuthnott-Garvock Group); the latter is transitional with the largely impermeable lavas of the Ochil Volcanic Formation (Browne et al., 1987).

The sandstones of the Stratheden Group and Scone Sandstone Formation are proven aquifers in Fife. The structure of the aquifer outcrop is largely controlled by extensional faulting, with much of the aquifer being fault-bonded by the SW-NE trending Fernie and Dura Den faults. The Scone Sandstone Formation is classed as highly productive (MacDonald et al., 2004) with normal operating yields in the Devonian sedimentary rocks in the range of 5 to 15 litres/second [l/s] (Ó Dochartaigh, 2006). Groundwater flow is dominated by fracture permeability, even in the sandstone formations where intergranular permeability is relatively high and anisotropic, suggesting that there may be preferential horizontal flow along bedding planes (Ó Dochartaigh, 2006). Measurements of the intergranular porosity and permeability are not available for the Scone Sandstone Formation, but measurements at one borehole in the Lower Devonian sedimentary rocks in the Strathmore Basin (Fig. 1.2) at depths of between 7 and 147 m below ground level indicate a median porosity of 14 % and a median hydraulic conductivity of 0.0014 m/d [metres/day] (Ó Dochartaigh, 2006), which is similar to the Upper Devonian Glenvale Sandstone Formation in Fife (Ó Dochartaigh, 2004). The transmissivity of the Arbuthnott-Garvock Group (undivided), which contains the Scone Sandstone Formation, is given by Ó Dochartaigh et al. (2006) as between 4 - 290 m^2/d with a median value of 34 m^2/d (6 samples), while specific capacity ranges between 2 and 258 m^3/d/m with a median of 25 m^3/d/m (7 samples). Storage in the Lower Devonian aquifer is given as an average value of 0.002 (5 samples).

Little is known directly about groundwater flow in the Devonian volcanic rocks, although fracture flow is likely to dominate, except along the boundaries of individual lava flows which may be preferentially weathered, increasing the local intergranular permeability. High flow rates in the Ochil Volcanic Formation occur in boreholes in Dundee. Intercalations of volcanic rocks within the Scone Sandstone Formaiton are likely to restrict groundwater flow both vertically and laterally.

The Knox Pulpit Formation, together with the overlying Kinnesswood Formation, generally has the highest porosity and permeability of the Upper Devonian of Fife. The underlying Glenvale and Burnside formations tend to have lower permeability, but provide significant yields in some cases. Public supply boreholes abstracting from the Knox Pulpit and Kinnesswood formations, such as Freuchie and Newton of

Lathrisk, provide yields of up to 46 l/s, while those constructed in the Glenvale and Burnside Formations, such as Kinneston and the Kinnesswood boreholes, do not generally yield more than 28 l/s. The highest permeability in each of the Upper Devonian units tends to be in the uppermost 10 to 15 m of the saturated zone, where weathering has significantly increased secondary permeability (Foster et al., 1976). Porosity in the aquifer is generally relatively high. The sampled values range from 4 to 30%, with a geometric mean of 19%. Laboratory measurements of pore-size distribution and centrifuge specific yield for the same core samples show that the specific yields of sandstones with porosities exceeding 20% are likely to reach 12 to 15%. Sandstones with porosities of less than 20% tend to have more variable pore size distributions and may have specific yields of less than 5% (Foster et al., 1976). Hydraulic conductivities of 0.5 m/d (7 samples) are reported for the (undivided) Upper Devonian aquifers in Fife (Ó Dochartaigh et al., 2015). Transmissivity in the Knox Pulpit Formation is generally around 200 m^2/d. Very high transmissivity values in the Kinnesswood Formation (Kinnesswood borehole) may be explained by the fact that the area is highly faulted. In comparison, testing of the Kinneston borehole (Glenvale) gave a very low transmissivity of only 12 m^2/d (Ó Dochartaigh et al., 1999).

The higher permeabilities at outcrop are not representative of the deeper subsurface due to compaction and mineralisation. Groundwater flow can be dominated by fracture permeability, even in sandstone formations where intergranular permeability is relatively high. However, the majority of fracture inflows occur within 60 to 70 m of the ground surface. At greater depths, secondary voids also occur, but to a lesser extent. In the Kettlebridge borehole, for example, which is 123 m deep, only 10% of the total yield derives from below 100 m (Foster et al., 1976). Theoretically, fractures are likely to be closed (or absent) at depths of one kilometre or more beneath the central Midland Valley (Browne et al., 1987).

The permeability of the most deeply buried sandstones in Fife is estimated by Browne et al. (1987) to be of the order of 0.014 m/d perhaps attaining 0.14 m/d within selective but isolated zones, with a transmissivity of 20 m^2/d for the Knox Pulpit Formation (at 500m depth). Core samples suggest that the hydraulic properties of the target formations become less favourable with increasing depths, as mineral overgrowths and pressure solution reduces the porosity. Borehole geophysics further suggest reduced permeability with depths (as inferred from deep boreholes in the Knox Pulpit Formation (and parts of adjacent formations). However, from a comparison with 4 m^2/d at Marchwood (1666 – 1725 m) and

Southampton (1729 – 1796 m), 7 m^2/d at Larne (968 – 1616 m) and >60 m^2/d at Cleethorpe (1100 -1498 m), the Upper Devonian/Lower Carboniferous aquifer in Fife could be capable of supporting the level of abstraction required for low enthalpy geothermal projects, although the abstracted fluids are likely to be mineralised. Since there is a lack of deep boreholes (> 500 – 1000 m) through these aquifers, and current measurements are derived from much shallower depths, it is not possible to predict flow rates and transmissivities with any accuracy.

3.4.3 ***Dura Den Fault permeability***

The role of the Dura Den Fault as a pathway for deep regional groundwater flow is currently unknown. It has been proposed that fractures and faults that are oriented parallel to the maximum horizontal stress orientation (sH_{max}) experience the lowest normal stresses acting across them, therefore fractures will undergo the least amount of closure and will thus be the most permeable (Heffer and Lean, 1993). However, Laubach et al. (2004) observed that at depths of >3 km, open fractures were not aligned parallel to the sH_{max} direction. Instead, fractures whose state of stress are close to the failure criterion are more likely to be conductive because of localized failure associated with a large shear component acting along the fracture surfaces (Barton et al., 1995). These fractures are termed 'critically stressed' fractures and are oriented approximately 30º to the maximum horizontal stress (sH_{max}) orientation (Rogers and Evans, 2002; Rogers, 2003).

Cherubini et al. (2014) suggest that an initial characterization of hydraulic properties of faults could be achieved through an analysis of the fault positions in relation to present-day *in situ* stress field, as applied by Sathar et al. (2012) for Sellafield. The current stress field of Scotland is described as near east-west extension (Baptie, 2010) with a NNW trend for the maximum horizontal compressive stress (Heidbach et al., 2008). Trending approximately north-east, the Dura Den Fault is oriented ~60-70º to the maximum horizontal stress orientation, hence it may not fall into the category of 'critically stressed fractures', although this requires local analysis (Sathar et al., 2012).

3.4.4 ***Hydrogeological model development***

A simple conceptual hydrogeological model arising from the geological model and regional review of the hydrogeology is presented in Figure 3.10. It focuses on the aquifer target depths and thicknesses which are important parameters, and incorporates the modelling of the Dura Den Fault damage zone. The aquifer properties are presented in Table 3.2 and are taken from published literature and reports, and work conducted by Town Rock Energy Ltd (see Section 4.1). Due the lack of available data on the behaviour of the aquifer at depth, the modelling explores some basic behaviour about the rates of recharge, changing hydraulic conductivity of units surrounding the aquifer, and the behaviour of the fault zones. It is not an accurate model of the rocks below Guardbridge, and the results therefore have large uncertainties, but it can be revised later if any test drilling programme goes ahead and relevant data become available.

FEFLOW® is a finite element model that simulates groundwater flow, as well as mass and heat transfer, through porous and fractured media (Diersch, 2005). As a geothermal heat modelling tool, FEFLOW® can simulate variable fluid density and heat transport, but some constraints on parameters such as porosity, permeability, aquifer thickness, sources of recharge and recharge rate are needed. For the purposes of this feasibility study, and in the absence of well constrained parameters, the simulations that have been performed test the behaviour of the aquifer under a range of reasonable conductivities (permeabilities), test the behaviour of the fault as a flow conductor or inhibitor, and test the range of conductivities required to get a well top flow rate of 5 l/s and 15 l/s flow (see section 4 for explanation of porosity, conductivity and chosen flow rates). The runs presented are from a 2D flow model, there is no heat flow modelling and only two vertical wells (GB-1 and ES) are included in the model runs; 3D modelling, heat transport and a deviated well (GB-2) can be included in the future, but it was not possible to develop these as part of this feasibility study.

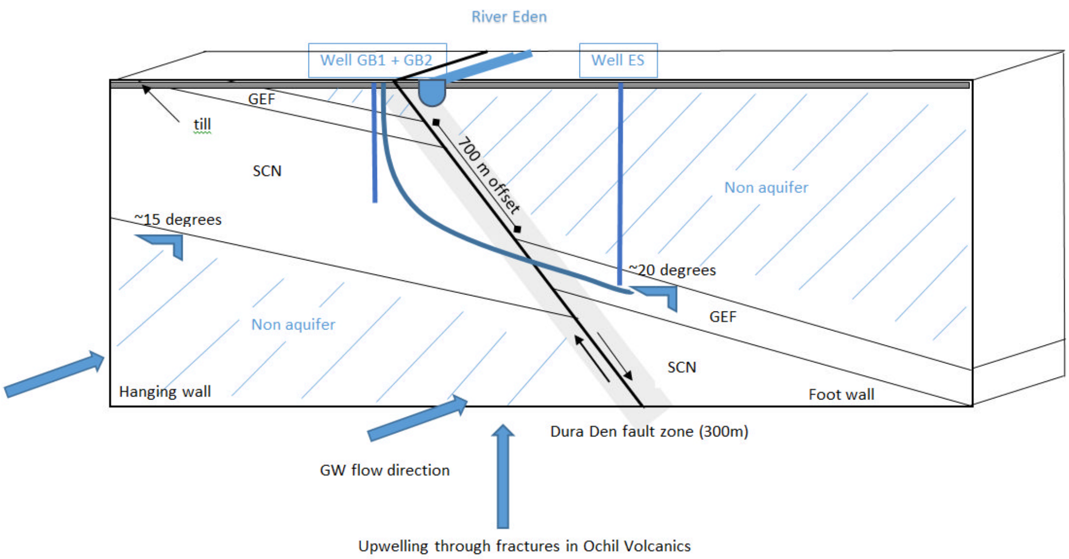


Fig. 3.10 Conceptual hydrogeological model based on geological model development in Section 3.1 Simulations do not model the deviated well orientation and this is shown for context only.

The model includes the Glenvale Sandstone, Knox Pulpit, Kinnesswoood and Scone Sandstone formations as the main aquifer units and they are assumed to be confined. The Anstruther Formation and Ochil Volcanic Formation are assumed to be non-aquifers and the possible impacts of fracture-dominated flow through, and from, the Ochil Volcanics is tested. The fault has been modelled as a discrete zone which can have a different conductivity than the surrounding aquifer rocks, and the fault zone can be further divided into a core and a damage zone with two different conductivities; these allow the influence of the fault zone on flow rates to be investigated.

Two boundary conditions (BC) were imposed: a fixed flux (Neumann) BC along the western (and parts of top/bottom) boundary representing recharge inflows, and a fixed hydraulic head (Dirichlet) BC in the eastern top corner of the model, representing the sea boundary. The 2D model is orientated at a 30^{o} angle to the fault plane. The sea boundary is located on the right-hand (eastern) side of the model, while the left-hand (western) boundary is facing inland towards the recharge area. The slice model considers the main aquifer formations and geometries, but as stated above, it should not be considered a true representation of the Guardbridge site because of the lack of data. In order to test different abstraction scenarios using the 2D slice model, the target abstraction rates (e.g. 15 l/s) had to be scaled according to the diameter of influence of the abstraction. Hence, the model cannot be used to assess the response at the well (e.g. draw down), but gives an integrated response of the aquifer area surrounding the abstraction. The results inform on the general behaviour of the aquifer and the fault, and therefore provide some useful insight into what parameters might be required for a productive and sustainable geothermal resource.

Model sensitivity simulations were conducted in steady state to test the model behavior and to select suitable parameter sets for abstraction simulations from those shown in Table 3.2. The wide variety of conductivities and transmissivities presented in Table 3.2 are from Town Rock Energy Ltd and published literature; the range of values reflects that the published literature is based on data from shallow boreholes, while the Town Rock Energy estimates are based on rock (matrix) properties at 800 – 1200 m depths, similar to the position of the target aquifers. Model parameterisation was initially based on the Town Rock Energy values, but these were then increased to test what level of fracture permeability is required to achieve the target yields. Since groundwater level data were not available for validation, a successful run was determined by keeping the hydraulic heads across the model to less than the topographic elevation of the land surface, which along the modelled slice ranges from 0 – 45 m. All the runs presented here assume that the well is pumping at 15 l/s (see Section 4 and 5 for the choice of this flow rate) over a period of 50 years.

Table 3.2. Parameters used in the FEFLOW® modelling and sources of values. K is permeability and T is transmissivity. Only the TRE values are used in the modelling. Sources are TRE: Town Rock Energy; Reference 1: Browne et al. (1987); Reference 2: Ó Dochartaigh et al. (2006).

		K m/d	Porosity %	T m²/d	Oper. Yield	K m/d	Porosity %	T m²/d	Oper. yield
	source	TRE	TRE	TRE	TRE	Ref. 1,2	Ref. 2	Ref. 2	Ref. 2
Knox Pulpit	Min	0.00134	10	0.134			4	12	4000
	Max	0.0134	14	6.7		0.06648	30	200	
	Median					0.05817	19	16.62	
Glenvale	Min	0.000134	8						
	Max	0.00134	9	0.067					2400
	Median								
Scone SS.	Min	0.000067	7	0.04				4	5
	Max	0.00134	11	0.201				290	15
	Median					0.0014	14	34	
Ochil Volc.	Min				5				
	Max				15				

Deep borehole data arising from oil and gas exploration report permeability in mD [millidarcys], whereas hydrogeological modelling uses hydraulic conductivity in m/d [metres/day]; Table 3.3 illustrates the terminology and units used in the hydrogeological modelling and well design and performance evaluation. By necessity, the ability for a fluid to flow through rocks will be discussed as both hydraulic conductivity and permeability and where relevant, a conversion has been provided.

An initial set of runs tested the impact of different recharge rates on the model behaviour and resulting water levels. Initially, it was assumed that 20% of the overall recharge in the catchment reaches deeper formations at the base of both vertical wells (Fig. 3.11A and 3.11B), with 10% coming from the top and 10% coming from the west. A comparison set of runs simulated lower recharge to deeper levels (10% overall), which is more realistic as discussed above (Fig. 3.12A and 3.12B). The next set of runs tested what hydraulic conductivities are required to achieve the target abstraction rate of 15 l/s. As part of this, the conductivities of the Ochil Volcanic Formation underlying the aquifers were varied to test the response of the aquifer to increased fracture flow from below (Fig. 3.13), and the fault behaviour was investigated by varying the width of the fault zone and its conductivity (Fig. 3.14).

In the majority of runs conducted, the overall abstraction rate of 15 l/s is greater than the combined recharge fluxes (negative DBC values greater than positive NBC values in Figures 3.11 - 3.13). This imbalance is typically compensated for by the release of water from storage within the aquifer, which represents an overall longterm depletion of the resource. The timescale for this is dependent on the storage capacity of the aquifer which is poorly known. Without re-injecting water into the aquifer, the resource would not be sustainable over decades. Well GB-1 is less sensitive to saline intrusion (blue flowlines in Fig. 3.11 -3.14), being further from the sea boundary in the model, whereas Well ES draws from the sea boundary because of its proximity (Fig. 3.11). The amount of saline intrusion increases as the input from deep recharge decreases (Fig. 3.12).

Table 3.3 A comparison of different units and terms for the parameters used in the hydrogeological modelling and the well design and performance evaluation.

Hydrogeological modelling (section 3)	Well design and performance (section 4)
Flow rates l/s (litres/second)	Flow rates l/s (litres/second)
Porosity (%)	Porosity (%)
Hydraulic conductivity m/d (metres/day)	Permeability mD (millidarcys)
Transmissivity m^2/day (metres^2/day)	Permeability thickness mDM (millidarcy metres)

Figure 3.11B and Figure 3.13 summarise the effect of changing the conductivity of the underlying Ochil Volcanic Formation for Well ES. In all runs, the aquifer has a hydraulic conductivity of 0.8 m/d (which is much higher than the matrix permeabilities given by Town Rock Energy Ltd and hence assumes flow in active fractures); in run 14.1, 14.2 and 14.3, the Ochil Volcanic Formation has a conductivity of 0.008 m/d (Fig. 3.11B), 0.08 m/d (Fig. 3.13A), and 0.8 m/d (Fig. 3.13B), respectively. If the latter has higher conductivities approaching that of the aquifer, ingress of sea water is reduced and duration of the resource is longer. Finally, the fault zone behaviour is presented in Figure 3.14 for Well GB-1. The first run (run 13.5) includes a 50 m wide fault zone with a conductivity of 0.8 m/d (Fig. 3.14A). The second run simulates a 100 m wide fault zone with a conductivity of 0.08 m/d (Fig. 3.14B), and the third run is a 100 m wide fault zone with a

conductivity of 0.8 m/d (Fig. 14C). The higher fault conductivities presents a fast pathway for water movement from deeper horizons towards the well, but the overall sustainability will depend on the volume of water available within these horizons from deep recharge routes.

In summary, based on a set of poorly constrained parameters required to model geothermal flow, the simple model presented here suggests that 15 l/s abstraction is possible given that the aquifer thicknesses used in the model are representative and assuming that there is sufficient fracture permeability to achieve the assumed hydraulic conductivities. The runs suggest that re-injection will be required to provide a sustainable resource for decades (to 50 years), but this does not address how temperature reduces with time. The current conceptual model underlying this 2D slice model requires that the Ochil Volcanic Formation is sufficiently conductive (due to fracturing) to permit deep water flows and that 10% of the overall recharge travels via deep flow pathways towards the coast. It also requires fracture permeability in the Glenvale/Knox Pulpit/Kinnesswood and Scone Sandstone formations. However, the properties of these formations and their behaviour at depths are so poorly understood, and further data are required before more robust conclusions about feasibility and sustainability can be drawn. The amount of saline intrusion modelled here is not realistic, because of the constraints and orientation of the 2D model, and further work on a 3D model with heat transfer and more constraints on the underlying parameters will significantly improve the model results.

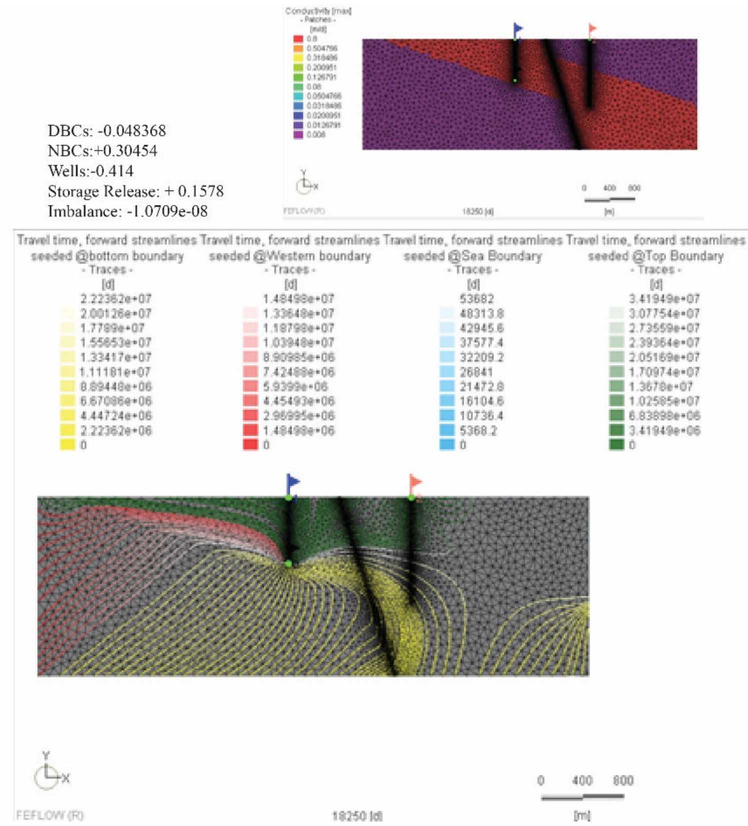


Fig. 3.11A Run 13.3 testing the influence of recharge rate on the aquifer behaviour at GB-1 well. Model run assumes 20% recharge to the deeper aquifer and K values of 0.8 m/d for aquifer and 0.008 m/d for other units.

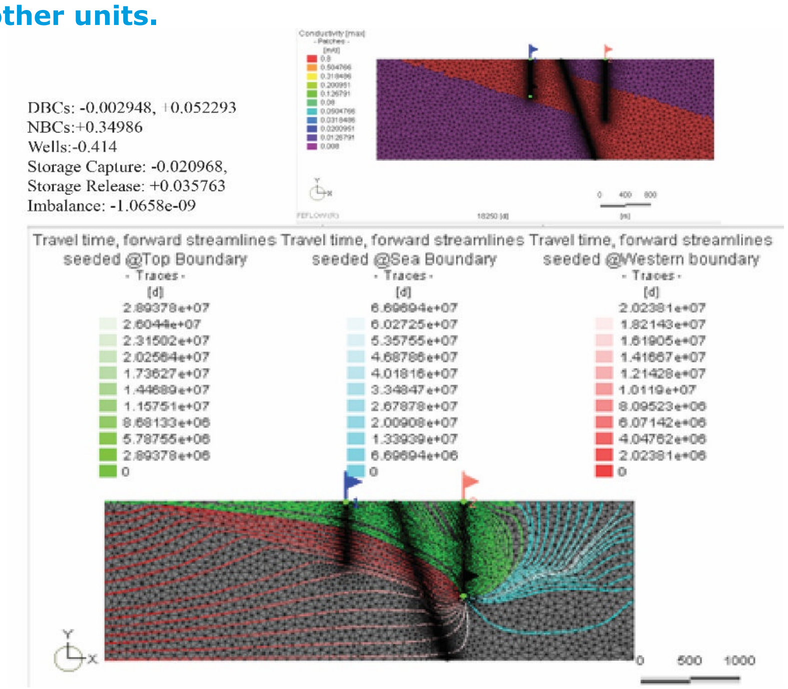


Fig. 3.11B Run 14.1 testing the influence of recharge rate on the aquifer behaviour at well ES. Model run assumes 20% recharge to the deeper aquifer and K values of 0.8 m/d for aquifer and 0.008 m/d for other units.

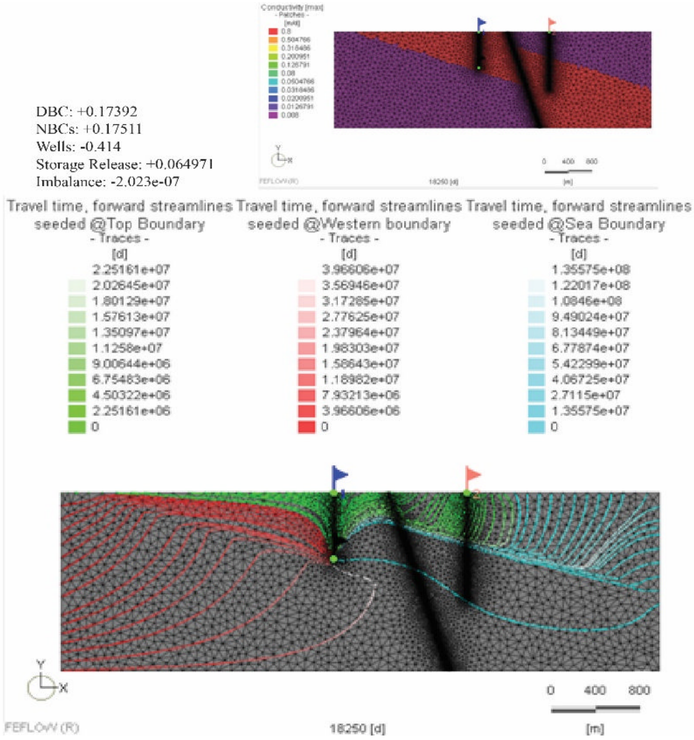


Fig. 3.12A Run 15.3 testing the influence of recharge rate on the aquifer behaviour at well GB-1. Model run assumes 10% recharge to the deeper aquifer and K values of 0.8 m/d for aquifer and 0.008 m/d for other units.

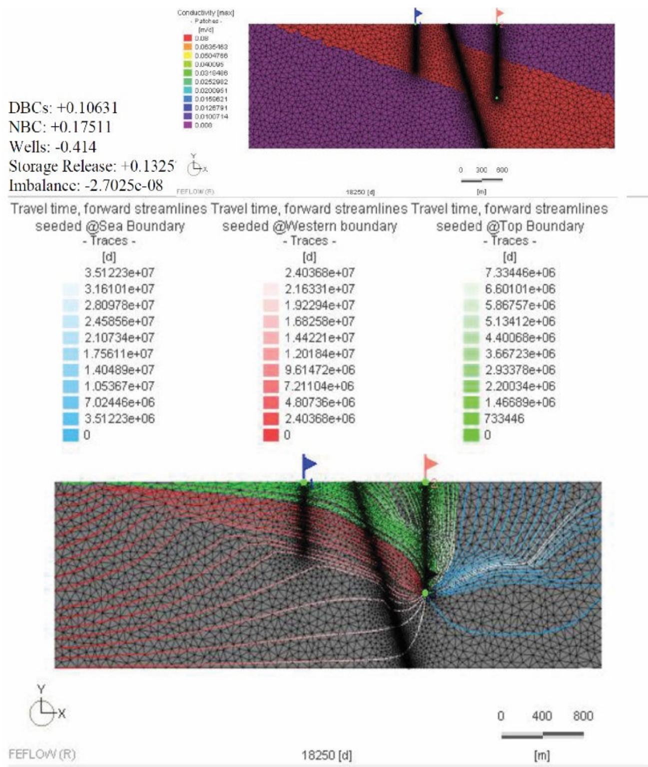


Fig. 3.12B Run 16.1 testing the influence of recharge rate on the aquifer behaviour at well ES. Model run assumes 10% recharge to the deeper aquifer and K values of 0.8 m/d for aquifer and 0.008 m/d for other units.

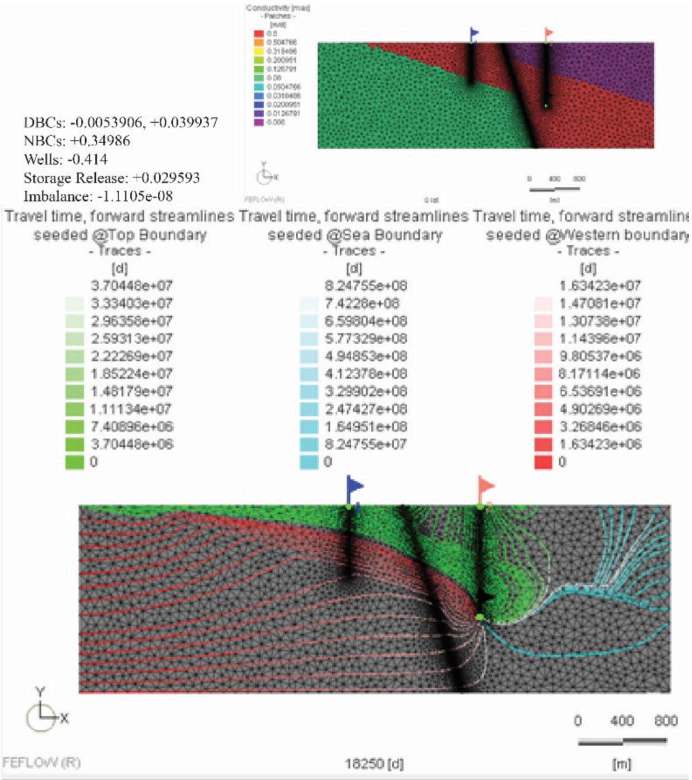


Fig. 3.13A Run 14.2 testing the influence of the Ochil Volcanic Fm (OVF) conductivity on the aquifer behaviour at well ES. K values of 0.8 m/d for aquifer and 0.08 m/d for the OVF.

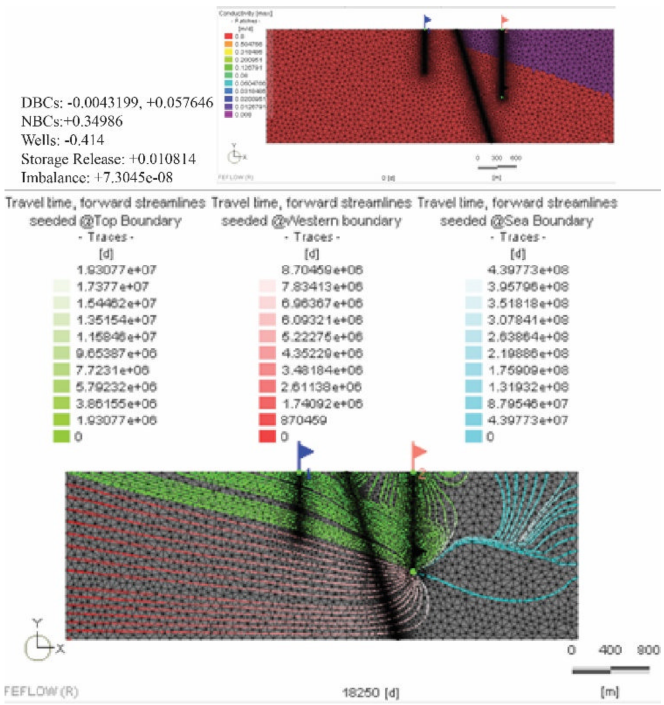


Fig. 3.13B Run 14.3 testing the influence of the Ochil Volcanic Fm (OVF) conductivity on the aquifer behaviour at well ES. K values of 0.8 m/d for aquifer and the OVF.

A.

B.

C.

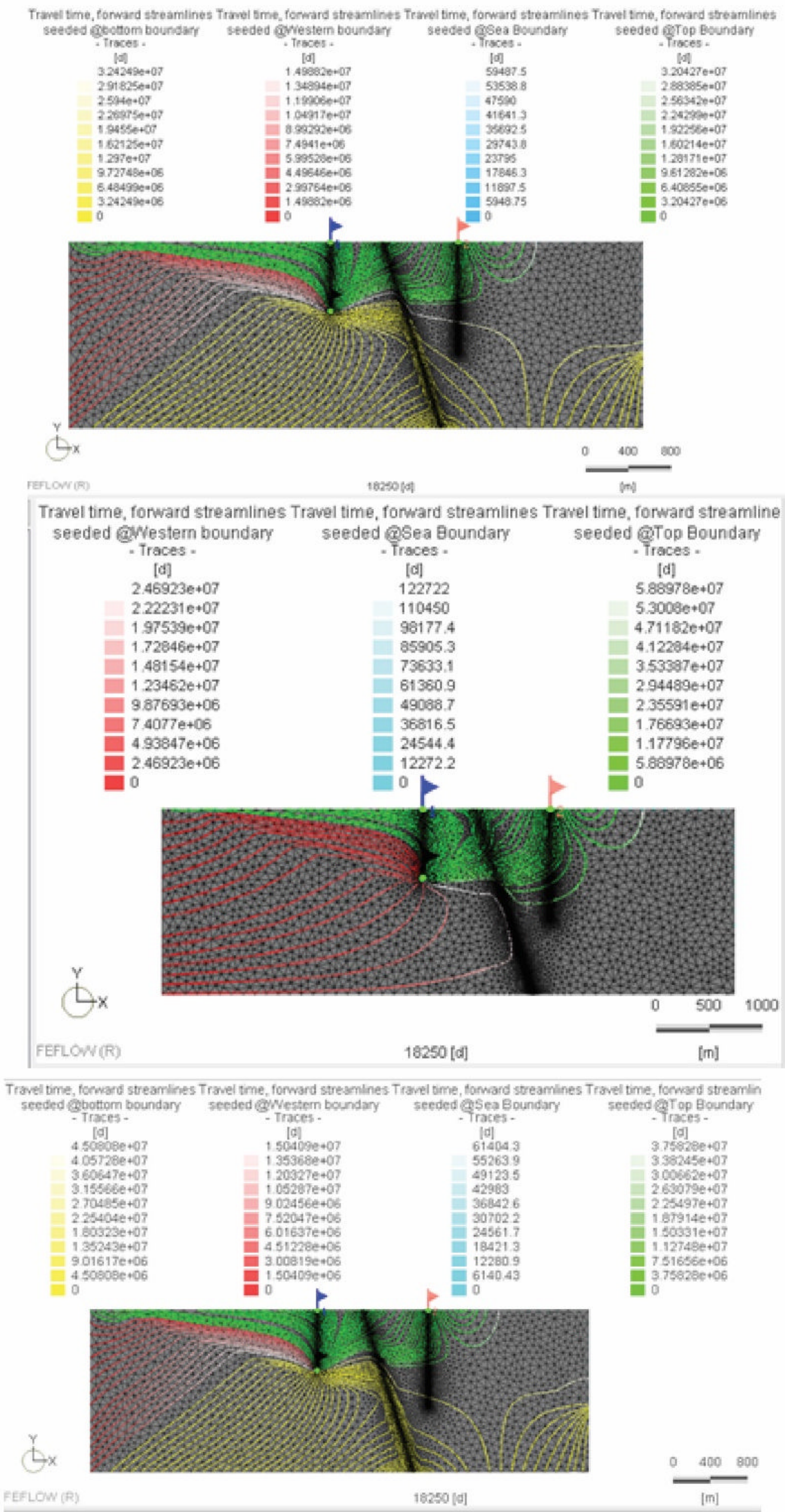


Fig 3.14. Simulations of fault behaviour. A. Run 13.5 with a 50 m wide fault zone and K = 0.8 m/d. B. Run 13.6 with a 100 m wide fault and K = 0.08 m/d. C: Run 13.7 with a 100 m wide fault and K= 0.8 m/d.

3.5 Play evaluation and de-risking

As the first deep geothermal well in the Midland Valley, a Guardbridge well has significant value in addressing the geologic uncertainties and risks for the HSA play (prospects) across the region as outlined in the previous sections. A successful well with flow at economic rates would be a major boost to geothermal heat exploitation throughout the Midland Valley. A negative result will have varying impacts regionally, depending on the reason for failure.

Outwith this feasibility project, Town Rock Energy (TRE) have produced regional Common Risk Segment maps for HSA targets in the Midland Valley; example maps are provided in Figures 3.15 – 3.17. The study covers an area from Arbroath and the east coast of Fife to Stirling and Motherwell in the west and North Berwick in the southeast. Publicly available well data, including wireline logs and core, have been used to evaluate porosity and permeability trends with depth. Previous studies on geothermal gradient (Gillespie et al., 2013) have been verified for these wells and a temperature estimate with depth has been calculated. Gross depositional environment maps have been made by University of St Andrews for the TRE project, based on published research. This integrated risk mapping project aims to predict areas where rock type, permeability and temperature align to give favourable conditions for warm water flow from aquifers. These are very much regional maps, and any one geothermal prospect will carry local risks and uncertainties which can be investigated with a variety of geologic and geophysical techniques.

The sparsity of borehole data, and of good quality stratigraphic and sedimentological logs and core data, means that there is significant uncertainty in the Common Risk Segment Maps. For example, the primary target intervals, the Knox Pulpit and Kinnesswood formations, are found at outcrop and in a couple of deep wells, but there are no aquifer quality data for these intervals in the shallower subsurface (i.e. less than 1500 m depth). To overcome this, how porosity changes with depth has been averaged across all Carboniferous strata penetrated in wells after detailed analysis showed that this was a reasonable reduction of the data. Data from Carboniferous successions are used to model Devonian rock characteristics because those are the only available data in this region of the Midland Valley.

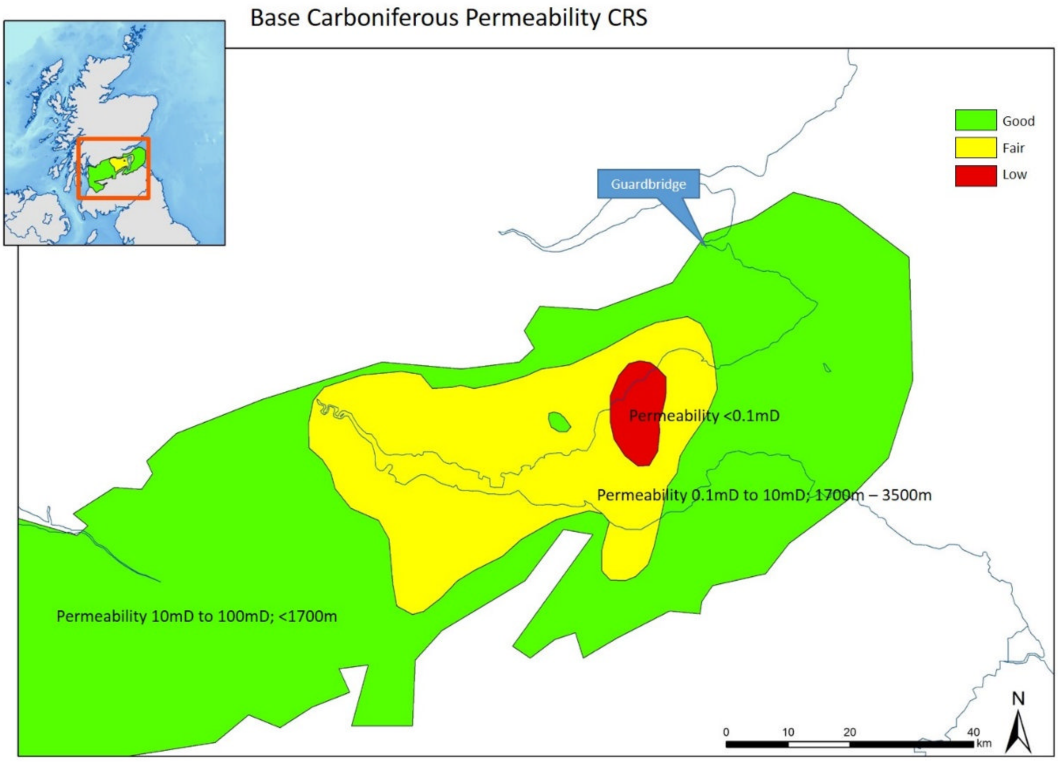


Fig. 3.15 Matrix permeability quality for sandstones in Kinnesswood and Knox Pulpit formations with depth to horizon as the primary control. Permeability and porosity predictions based on core and wireline data.

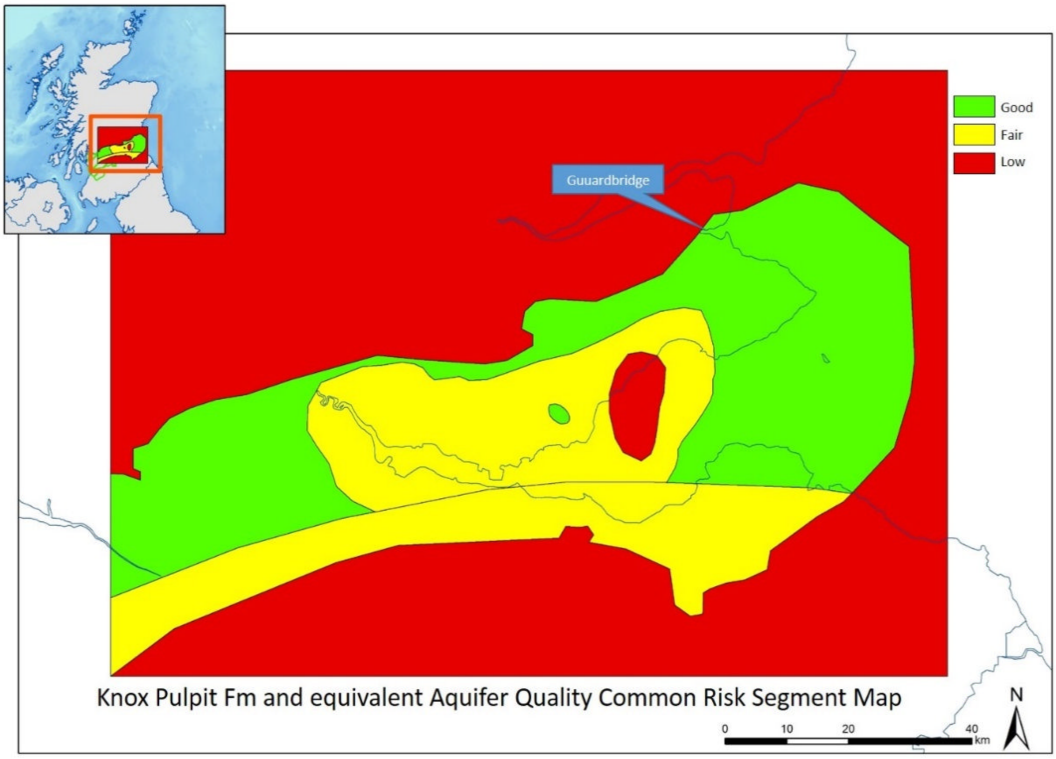


Fig. 3.16 Combined permeability and depositional environment map of the Knox Pulpit Fm. Green segments represent favourable characteristics due to shallow depths of burial. Red areas represent non-deposition or erosion, unfavourable facies, or poor permeability due to depth of burial.

The most critical factor in proving the HSA play in the Midland Valley is to demonstrate that economic flow rates can be achieved from the aquifers. Flow will be determined by matrix permeability, and any increased permeability associated with natural faults and fractures in the aquifer. Future wells can be optimally designed to exploit these areas of increased flow. At present, deeper targets with temperatures in excess of 60 °C are likely to have very poor matrix permeability based on the available data, and therefore uneconomic flow rates.

New rock properties data from a well at Guardbridge, designed to target hot sedimentary aquifers at relatively shallow depths and temperatures of 25 °C to 45 °C, will provide valuable tests of the assumptions that have been made with regard porosity and permeability depth trends. A positive result with significant flow rates of water from a defined interval at Guardbridge will provide critical datasets on flow and rock properties that are regionally transferable, and will significantly reduce the risks of exploration within the Central Belt of Scotland.

The following sections look at the specific regional impact of each of the three well targets.

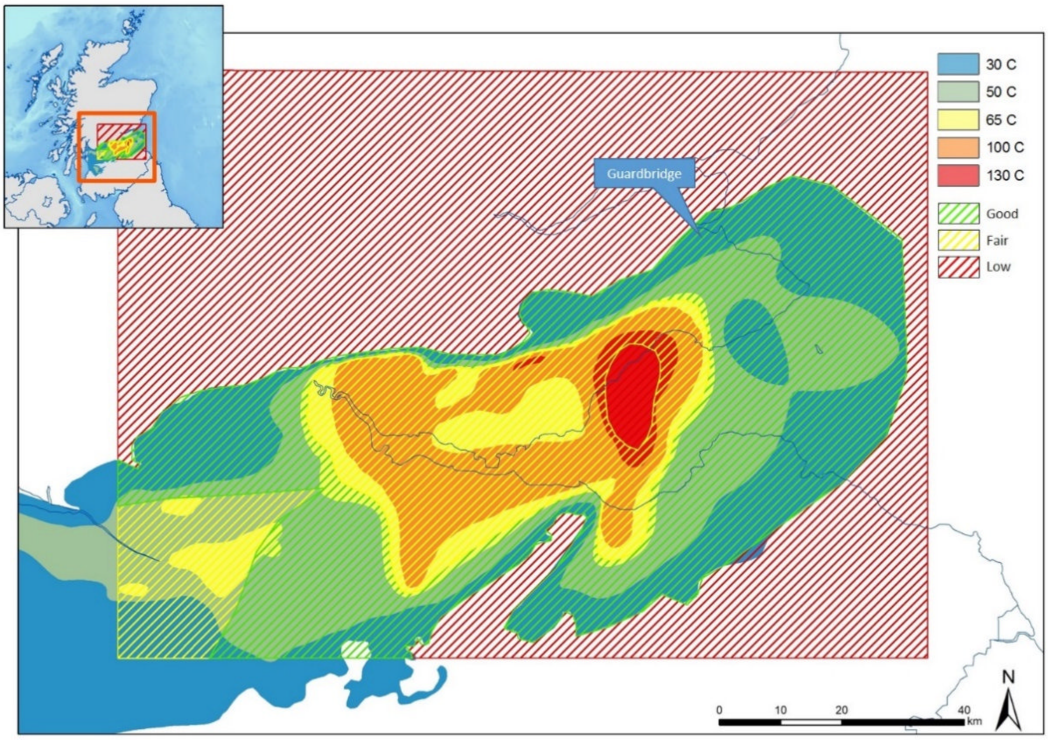


Fig. 3.17 Combined map of estimated aquifer quality (see Fig. 3.5) and predicted temperature.

3.6 Regional impact of Guardbridge wells

3.6.1 *Well GB1 – vertical well on site*

This well is located within the Guardbridge site and targets the upper units of the Glenvale Sandstone and the Scone Sandstone formations (Fig. 3.7). Drilling this well would increase our knowledge and understanding of the local and regional stratigraphy by providing lithology and formation thickness data which could be used to improve the regional mapping of the Scone Sandstone Formation in the northeast Midland Valley and update the Devonian HSA play. This play has not been mapped in detail at this time, though initial outcrop studies have been conducted and some surface porosity and thermal conductivity data have been collected by Town Rock Energy Ltd and the University of St Andrews.

The recovery of subsurface core would permit measurements of porosity and permeability to be made on fresh rock at a depth of around 500 m. These would be rare samples and would allow comparison with outcrop porosity and permeability data from locations in Fife, Perthshire, Tayside and Angus which may have been impacted by weathering and are generally less cemented and compacted. Identifying good porosity in the Scone Sandstone Formation would be encouraging for development of the play in, at least, the central and eastern Midland Valley.

Core samples would also allow identification and measurement of natural fractures, and whether the fractures are open or mineralised. A flow test would address whether the Scone Sandstone Formation can give economic flow rates of warm water. Devonian rocks that lie beneath Fife south of the Ochil Fault have generally been assumed to be too deep and too tight to produce water without stimulation. A successful flow from the Scone Sandstone Formation would trigger a review of where this Devonian target might be present at depth in Fife.

GB-1 also targets the Ochil Volcanic Formation underlying the Scone Sandstone Formation. Similar volcanic rocks provide potable water from wells in and around Dundee at potentially economic flow rates. A demonstration of significant water flow from the Ochil Volcanics with core data that showed open fractures would be encouraging for the development of the play. This would trigger a review of the play in the Stirling, Perth and Tayside area, especially where heat demand is high (e.g. Dundee, Perth and Stirling).

Bottom hole temperature data will be valuable in determining the geothermal gradient at the Guardbridge site, and establishing whether this is on trend with regional data or whether local variations are significant.

3.6.2 *Well ES – vertical well off site*

Well ES is located 1 km to the southeast of the Guardbridge site and targets the Upper Devonian Kinnesswood and Knox Pulpit formations (Fig. 3.8). Figure 3.18 provides an estimate of the extent of the Knox Pulpit Formation based on gross depositional environment maps (Robinson, unpublished data) in order to demonstrate the significance and regional impact of the geothermal project at Guardbridge. The Kinnesswood, and particularly, the Knox Pulpit formations have been identified as the primary HSA targets in Fife, and towards the south and west within the Midland Valley (Browne et al., 1987; Galbraith et al., 2013). Well ES1 also targets the Devonian Glenvale Sandstone and Scone Sandstone formations which have not been mapped regionally as HSA targets due to their great depth in most areas.

The Kinnesswood and Knox Pulpit formations CRS mapping relies heavily on the porosity depth trends and porosity-permeability cross plots from TRE's regional well study. Actual data from the two formations is sparse and the opportunity to acquire data at shallower depths will reduce the current level of uncertainties. The Guardbridge site is in a low risk, green, segment of the Kinnesswood and Knox Pulpit CRS maps (Figs. 3.26 -3.17) and so a positive result will support drilling in other green segments around the region.

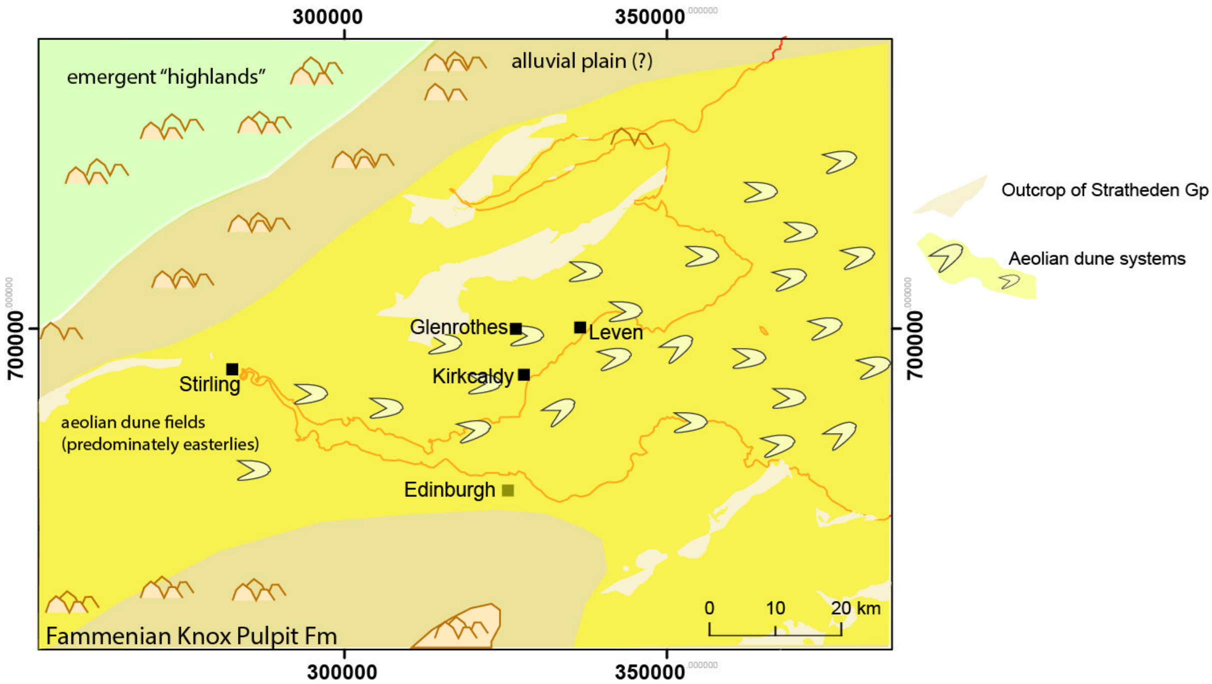


Fig. 3.18 Gross Depositional Environment (GDE) map for the Knox Pulpit Formation showing an estimate of the regional extent of the aeolian (and fluvial) deposit.

A successful result which demonstrates that there is a higher overall porosity for these formations at shallow depths than has been predicted, based on trends in other Carboniferous strata, would be significant regionally. Such a result may allow the green segment on the Kinnesswood and Knox Pulpit CRS maps to expand into the yellow segments which are currently downgraded due to loss of porosity and permeability at depth. Deeper, warmer water may be more productive in terms of flow rates than currently predicted.

Success in the older Scone Sandstone Formation and Glenvale Sandstone Formation would have similar impact to a positive result at GB-1; that is, encouraging a review of this geologic interval in the area of the Strathmore Basin to the north (Fig 1.2).

3.6.3 *Well GB-2 – deviated well on site*

This more complex well trajectory is a hybrid of the GB-1 and ES wells. The well head is located within the Guardbridge site and the well deviates so that the bottom of the well is located about 1 km to the southeast. The primary target is the undivided Knox Pulpit and Kinnesswood formations (in the vicinity of the Dura Den Fault (Fig. 3.9). This potentially combines the highest porosity and permeability aquifer with an area of natural fractures associated with the Dura Den Fault. In an optimal scenario, flow will be enhanced by a combination of open fractures and good aquifer permeability, and more of the aquifer will be accessed by drilling at a high angle to the formation; flow along the fault zone may increase the sustainability of the aquifer. However, the fault-related fractures could be cemented and that could result in reduced aquifer permeability. A positive outcome demonstrating good flow rates in the Knox Pulpit/Kinnesswood aquifer will have the same regional impacts as Well ES. In addition, demonstration of increased flow associated with the fault would trigger a review of fault and fracture distribution and stress history in the region in order to identify other areas where faulting may enhance productivity. Success in a deviated well would also inform future well design options. Optimising well design to achieve higher flow rates will be key to achieving economic feasibility for HSA wells.

4. HEAT SUPPLY

4.1 Predicted aquifer properties at wells

An estimate of aquifer quality, specifically rock permeability and downhole rock temperature, is required for each target interval to predict flow rate and water temperature at the surface for the different well completion designs.

Town Rock Energy Ltd (TRE) have previously constructed a regional database of petrophysical properties of sandstones in the target intervals. This draws on all publicly available deep wells in the Fife and Firth of Forth areas (Section 2.3). It carries significant uncertainty. For example, the Knox Pulpit Formation, which is generally agreed as the best target, is only found at depth in one well. However, experience in generating similar databases for oil and gas exploration has shown that the approach is a reasonable guide at this stage of evaluation.

For each well, the primary and secondary target intervals are identified with a depth range. The TRE depth versus porosity relationship is used to estimate an average porosity for the target sandstones. The porosity value is used to estimate the average permeability using a relationship determined from core plug measurements. The porosity-permeability relationship was developed prior to this study by TRE, based on new analysis of core data held by the British Geological Survey and earlier published data for the wells in Fife and the Firth of Forth area.

The average permeability for an interval is multiplied by the aquifer thickness penetrated in the well to give a total permeability for the target. There is large uncertainty in this estimate. At any one depth, the range in porosity might be 6 - 15 %, which gives a permeability range of 0.1 - 10 mD (two orders of magnitude) (0.013 -0.013 m/d in units of hydraulic conductivity). To simplify the evaluation, the most likely estimate has been used, except where the rocks are likely to have higher permeabilities (e.g. in the Knox Pulpit and Kinnesswood formations and in the zone across the fault in GB-2, where two scenarios are evaluated).

TRE have used published temperature depth plots for the Midland Valley (Gillespie et al., 2013) and verified the trend by reviewing the raw well log temperature and circulation data in the prior petrophysics study.

4.1.1 ***Well GB-1***

This well (Fig. 3.7) has a thin Scone Sandstone Formation target which has probably been up to 4000 m deeper at maximum burial before being uplifted. Taking an optimistic porosity of 11 % from a trend that does not allow for the deeper burial effects gives 1 mD (0.0013 m/d) of permeability and so 30 mDM

(0.039 m^2/d) of permeability thickness (transmissivity) for the target interval. If the burial history is assumed to degrade porosity then it will be closer to 6%, with negligible permeability. There are secondary, tighter, targets in the overlying Glenvale Sandstone Formation, which may offer another 150 mDM. The volcanic rocks below 700 m in the GB-1 well may have reasonable flow rates, based on some shallow potable water wells in Dundee where natural fractures and porosity deliver 5 - 15 l/s of water. This cannot be tested without drilling. Temperature in the primary target interval is estimated at 24 ^{o}C.

4.1.2 ***Well ES***

All rocks below 600 m could contribute to flow in this well. Primary targets are found at 700 - 800 m in the Kinnesswood and Knox Pulpit Formation and 1000-1050 m in the Glenvale Sandstone Formation (Fig. 3.8). Porosities gradually decrease over the target intervals from 11% in the Kinnesswood Formation to 7 % in the Scone Sandstone Formation. Permeability decreases from 1 mD to 0.05 mD (0.0013 to 0.000066 m/d), although the Knox Pulpit Formation may see 10 mD on average (0.013 m/d), based on the quality seen in outcrop. This gives permeability thicknesses of 100-1000 mDM in the primary target of the Kinnesswood/Knox Pulpit aquifer and 200 mDM over all the remaining intervals. This well has a significantly higher chance of achieving natural flow from the rocks than GB-1. Temperature in the primary target interval is estimated at 27^{o}C.

4.1.3 ***Well GB-2***

This deviated well crosses the Dura Den Fault (Fig. 3.9). The thickness of the fault damage zone is estimated (see section 3.1) and the better quality Kinnesswood/Knox Pulpit aquifer is also present in the fault damage zone. The interval is estimated to have a porosity of 12 % and a permeability of 10 mD (0.013 m/d), though natural fractures in the fault zone could enhance this to an average of 100 mD (0.13 m/d). Two alternatives are evaluated: the sandstone in the primary target has 2200 mDM, or with the addition of open natural fractures in the fault damage zone, there may be over 10,000 mDM. There is an alternate reduced flow model arising from the fault acting as an inhibitor of flow due to cementation from fluids, which reduce the rock porosity and permeability. The deeper zones in this well away from the fault zone are not predicted to make a significant contribution. Temperature in the primary target interval is estimated at 24^{o}C.

4.2 Well completion options and performance

Two alternative well designs for extracting heat from the subsurface have been evaluated: using a Heat Pump and by direct Aquifer Production.

A **heat pump design** will circulate water down a casing string which is run to the bottom of the well. Water is warmed to rock temperatures and then brought to surface via plastic tubing inside the casing. All intervals are cased off and there is no production of aquifer water at the surface. This is essentially similar to a Ground Source Heat Pump but at greater depth. To recover economic amounts of energy from heat pump wells, there is a balance between the rates of circulation, heating within the well tubing, and cooling as the water comes to the surface through decreasing rock temperatures.

An **aquifer production design** produces water from the rocks directly and brings it to surface with the aid of an Electric Submersible Pump (ESP) to allow for varying drawdown on the reservoir. These wells have a casing string isolating the shallow geology and then a protective slotted liner to reduce the risks of hole collapse and sand production from the aquifer interval as the pressures on the formation are reduced. The ESP will be run on production tubing or plastic pipe to the shallow casing shoe. There is a balance in aquifer production wells between the drawdown required to achieve higher flow rates, the increasing risk of sand production at high drawdowns, and the power required to drive the ESP. There are also considerations of well sustainability at higher flow rates, both for pressure support from the formation and for heat.

4.2.1 *Well GB-1 design*

An aquifer production well at GB-1 has a very low predicted flow rate due to the limited permeability thickness. Producing at a drawdown equivalent to a vacuum across the rock face produces 0.6 l/s flow which is an order of magnitude too small. **Therefore, GB-1 is not a viable aquifer producer.**

A heat pump well at GB-1 can only achieve small increases in temperature of about 1-3 ^{o}C at circulating rates of 1 to 5 l/s. The downhole temperature is too low and the circulation too fast to achieve sufficient heating. Figure 4.2 shows the temperature profile in the well at different circulation rates and input temperatures. **GB-1 is not a viable heat pump well.**

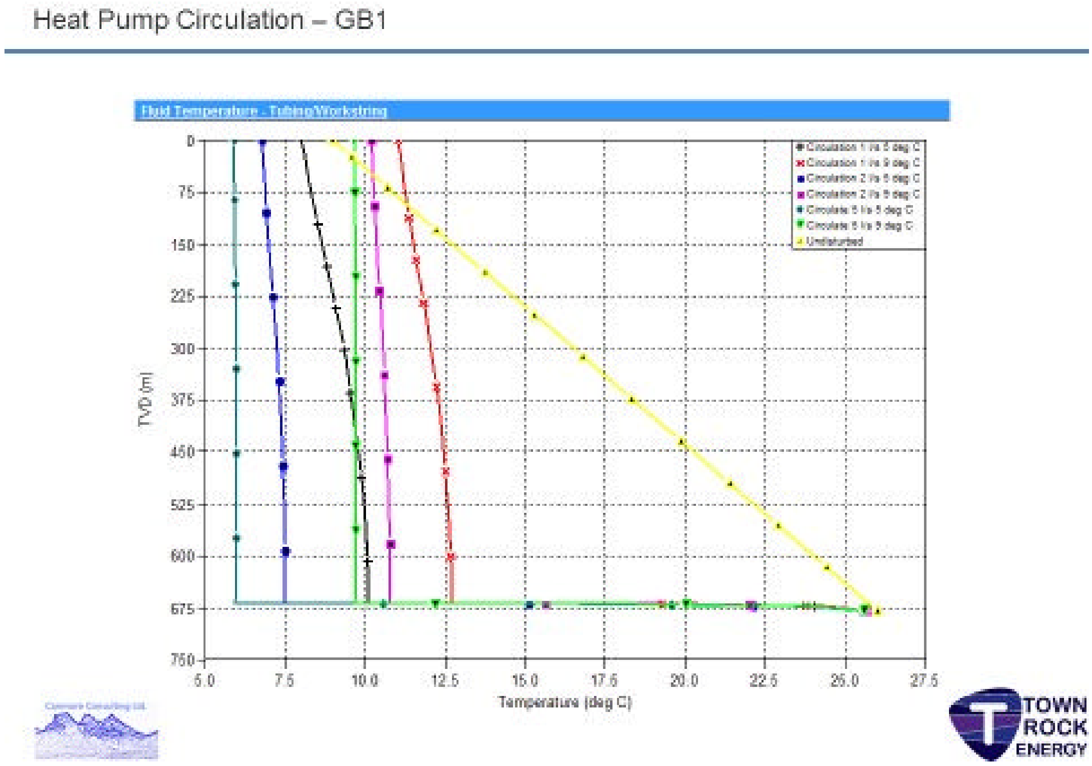


Fig. 4.1 Model temperature results for heat pump well completion at GB1.

4.2.2 *Well GB-1 design (deeper option)*

Well GB-1 enters volcanic rocks at about 700 m below the ground surface and these rocks can be expected to be present to a depth of about 2500 m (Fig. 3.3 and 3.7). A heat pump circulating well, with a pump located at 2500 m, has been modelled and predicts a rock temperature of 72 °C at the base of the well. Figure 4.2 shows well temperature profiles at different circulation rates and input temperatures for a heat pump design. At low circulation rates of 1 l/s, fluid temperatures of 50 °C can be achieved at well bottom, but there is significant cooling because the fluid comes to the surface to about 17 °C. At higher circulation rates, downhole temperatures are lower (20 °C for a circulation rate of 5 l/s), but cooling is less and reasonable surface output temperatures about 5 °C higher than input temperatures can be achieved. Optimising tubing size and insulation, well rates and input temperatures can all influence performance. Circulation at 8 l/s to a depth of 2500 m in 114 mm pipe will give a surface temperature increase of 5 °C between input

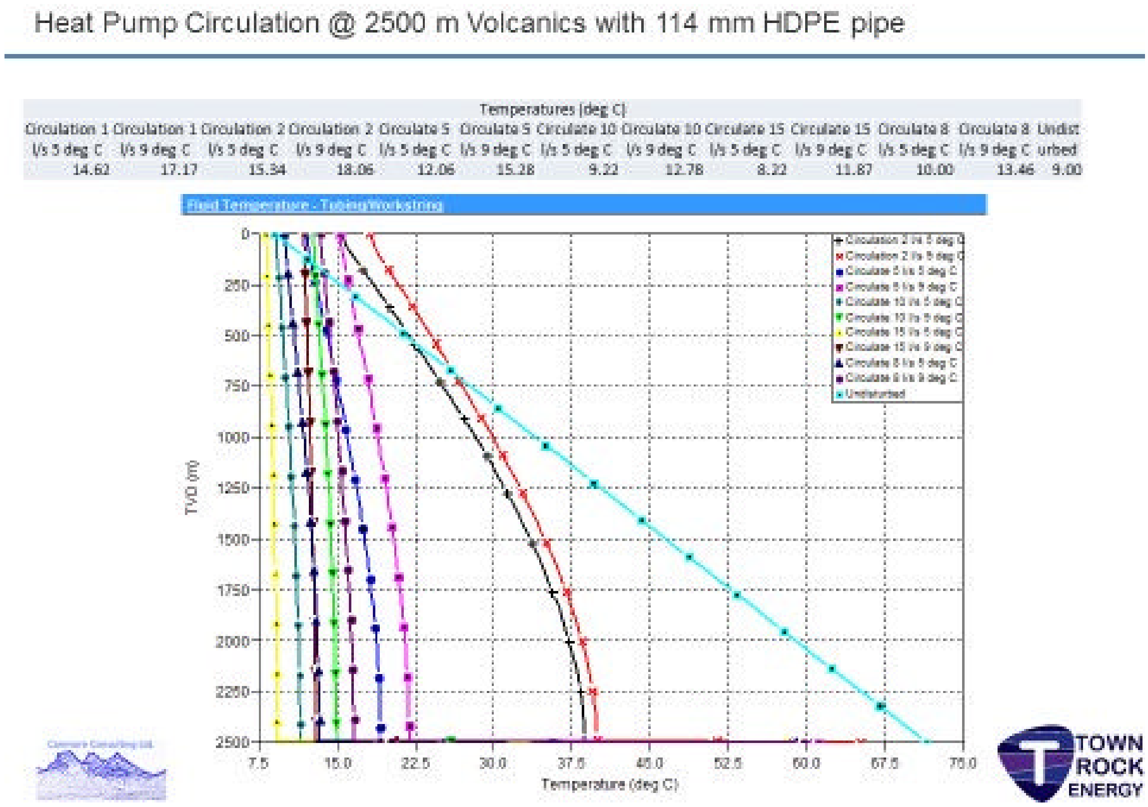
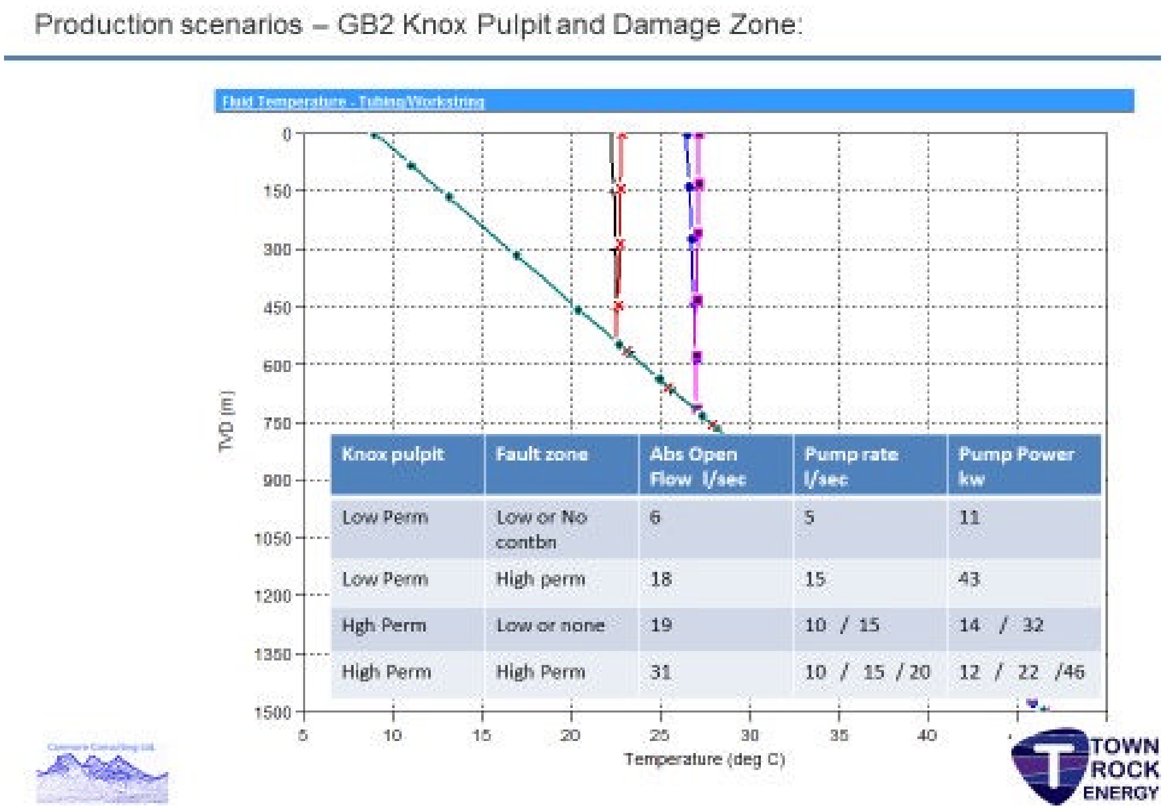


Fig. 4.2 Model temperature results for heat pump well competion at GB1 at 2500 m depth.

and output, where input temperature is between 5 °C and 9 °C. **GB-1 deeper option may be viable as a deep circulating heat pump well.**

4.2.3 ***Well ES design***

An aquifer production well at ES has very low flow rates unless the higher expected permeability model is used. In the 1000 mDM case, a flow rate of 5 l/s is achievable with a 20 kw ESP, giving 28 °C water temperature at the well head. There is insufficient rock quality to give higher rates of flow. **ES may be a viable aquifer producer at low rates,** but with the impact of additional costs attributed to the well's off-site location and the risk of lower productivity, it is not considered further. ES as a heat pump circulating well has similar characteristics to GB-1. It is too shallow to give sufficient temperature increases at the rates required. **ES is not a viable heat pump well.**



Knox pulpit	Fault zone	Abs Open Flow l/sec	Pump rate l/sec	Pump Power kw
Low Perm	Low or No contbn	6	5	11
Low Perm	High perm	18	15	43
Hgh Perm	Low or none	19	10 / 15	14 / 32
High Perm	High Perm	31	10 / 15 / 20	12 / 22 /46

Fig. 4.3 Model output temperature results for an aquifer production well at GB2 with tabulated permeabilities and flow rates.

4.2.4 ***Well GB-2 design***

GB-2 has not been considered as a heat pump circulating well, as there is no value in having a deviated well with this design. An aquifer production well can realise potentially economic flow rates because the Kinnesswood/Knox Pulpit aquifer and the fault damage zone can both have a positive effect on flow rate. A low permeability will yield 5 l/s flow rates with an 11 kw ESP. There are several combinations of Kinnesswood/Knox Pulpit and fault damage zone permeabilities that can deliver a flow rate of 15 l/s flow with an ESP power in the range of 22 – 43 kw. There is scope for flow of 20 l/s or higher, but at power inputs greater than 45 kw for the ESP. Output temperature will be between 23 °C and 27 °C, depending on the source of the dominant flow. **GB-2 is a potentially viable aquifer production well.**

Figure 4.3 shows the temperature profiles in the well for different pump rates for production and from two depths, equivalent to the Kinnesswood/Knox Pulpit aquifer and the fault damage zone.

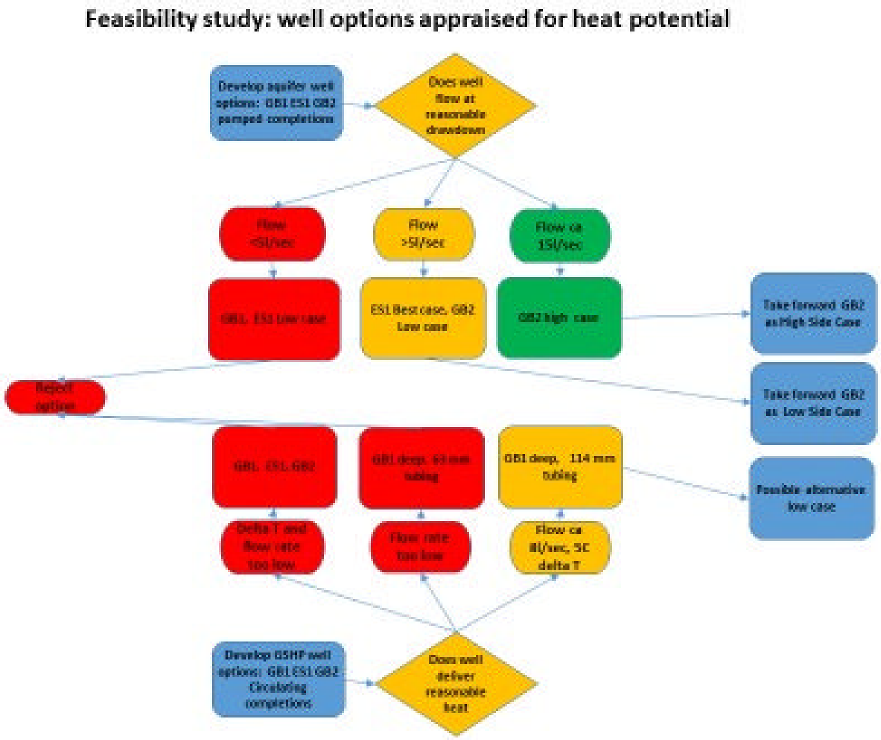


Fig. 4.4 Model output temperature results for an aquifer production well at GB2 with tabulated permeabilities and flow rates.

The flow diagram (Fig. 4.4) summarises the options and conclusions of the completion design, and the flow and temperature modelling with regard to each well location. **The GB2 deviated well is taken forward for well design and cost estimation with two flow rate scenarios: 5 and 15 l/s**.

4.3 Well design and drilling

This section addresses the construction of the GB2 well (Fig. 4.5). Appendix A includes options for drilling wells GB1 and ES1. Well GB2 would be a deviated shallow well that aims to drill through the Dura Den Fault to achieve flow from the intersection of the fault damage zone and the Knox Pulpit and Glenvale Sandstone formations. The total depth of the well is planned to be 1000 - 1200 m.

A conductor is required to get into hard rock through the surficial glacial and shore deposits. This is estimated to be 10 – 20 m and would be driven by the size of the other casing strings. The directional path would have to start at a true vertical depth (TVD) of 200 m, increase to 20° of inclination by 400 m depth, and up to 60° of inclination by 800 m. The directional planning has not been developed in any detail at this point. It is possible that the well site may change location due to ongoing building development at Guardbridge and any reconnaisance

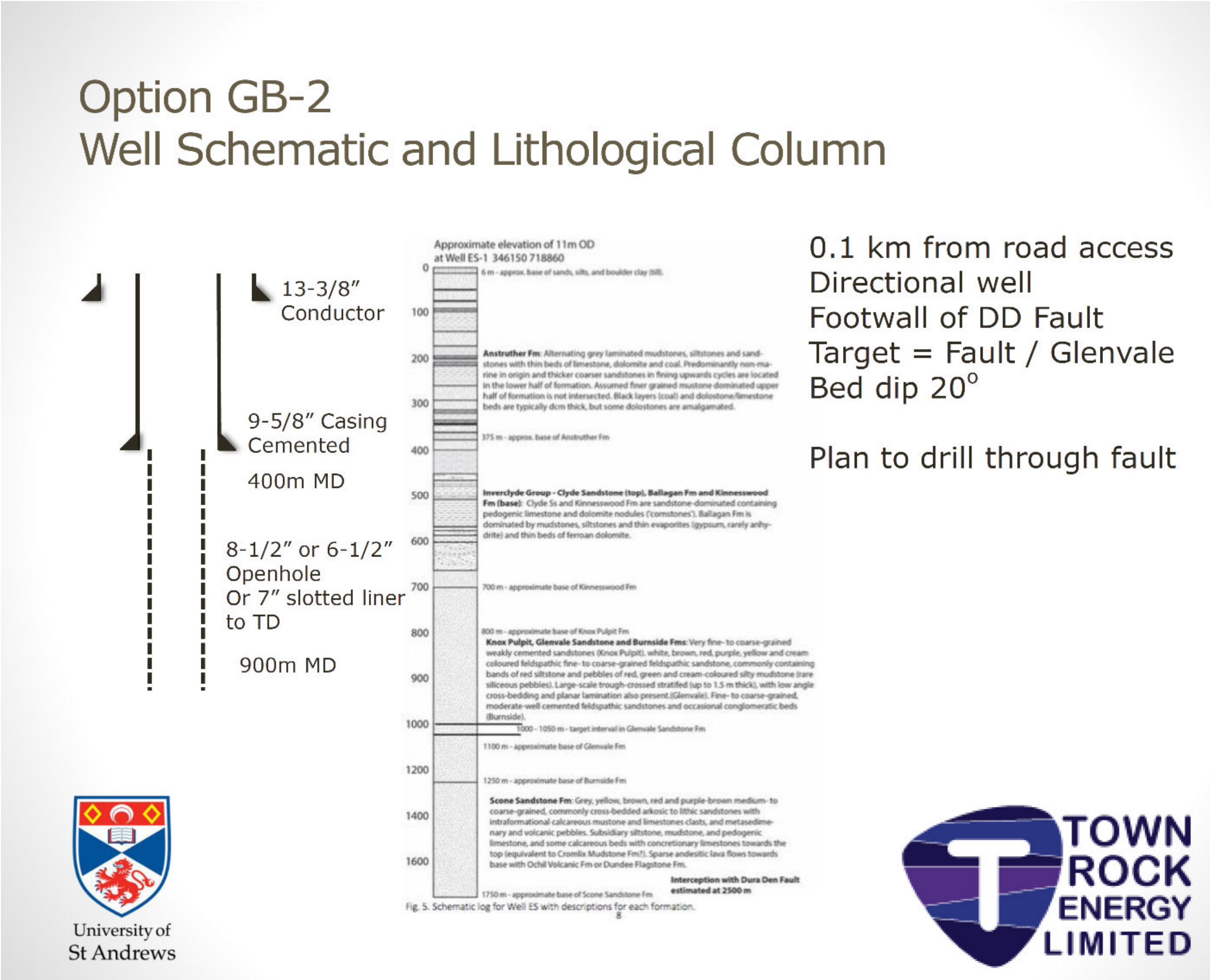


Fig. 4.5 Schematic lithological column and casing design for GB-2.

geophysical surveys undertaken as part of Phase 2, which would identify the fault location, orientation and fault damage zone in more detail. The final choice of the GB-2 well location will be influenced by the required space to establish a constant deviation angle before entering the fault damage zone. A 9 5/8″ casing would be set between a measured depth (MD) of 400 – 800 m; this would be cemented to the surface and well control equipment could be installed.

The next hole section is through the target intervals and will include coring runs and logging; this may require further directional drilling, at least with stabilisers to hold the angle. Cores would be taken to allow measurements of porosity and permeability before the drilling and logging are complete. There is a possibility that logging and coring will demonstrate that the well is not capable of producing sufficient flow to be economic. The drilling could be suspended at this point, for the so-called "dry-hole" cost.

If, based on core and logs, the well has aquifer production potential, then flow rates will need to be tested. A full test will require installation of an ESP to achieve drawdown. With increasing drawdown there is an increased risk of sand production or well bore collapse, which would compromise the test and may require re-drilling prior to operating for long term production. Hence, it is recommended that any decision to test should be seen as a decision to complete the well for production. A slotted liner will be run to the well total depth to protect against wellbore collapse and mitigate sand production. The ESP would be run within steel pipe or plastic and once installed, the drilling rig would be demobilised as flow testing can be undertaken without the rig. Water clean-up, or capture and disposal, will be required in the test period and extensive water and particulate geochemistry would be conducted during this stage. Figure 4.6 summarises a decision tree for the development of well GB-2.

4.4 Well costs

The size and capability of the rig required to drill a deviated well determines the daily costs. An undersized rig, or a rig that is reaching its limitation, will lead to more non-productive time (rig breakdown time), issues with torque and drag on reaching the maximum depths, and may have to stop before reaching the objective or be unable to run or lift casing. After discussions with a number of operators for

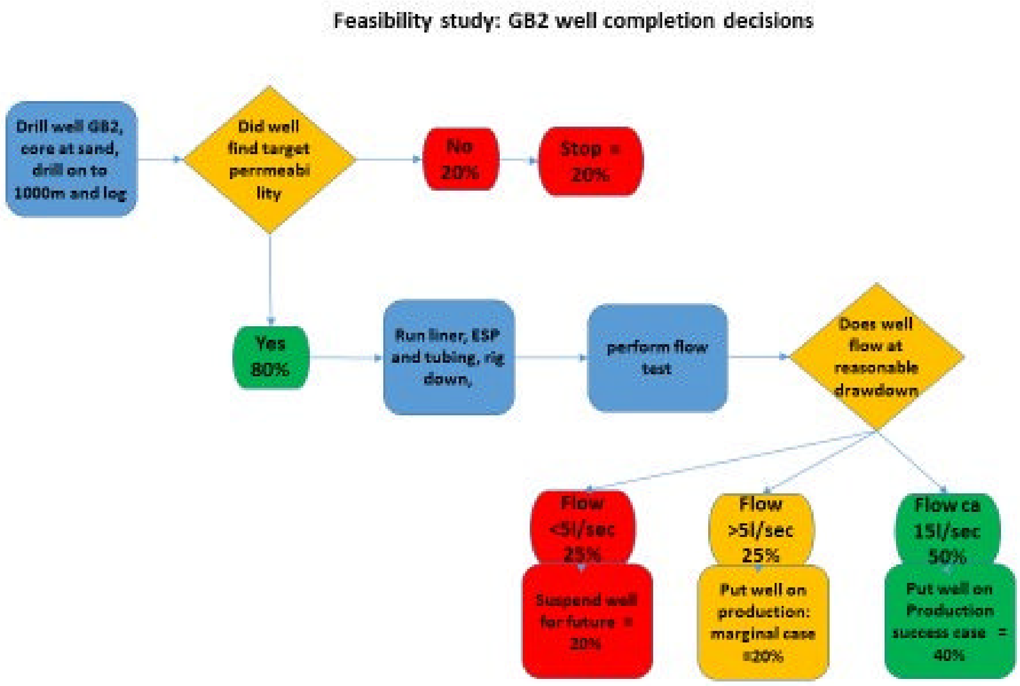


Fig. 4.6 Decision flow chart for the completion of GB-2 well.

this well, a 100 tonne rig capable of 24 hour operations, drilling with a closed loop mud system and with well control equipment, is recommended.

Cost estimation is based around a time versus depth curve for the well which fixes the costs associated with daily rates, such as the rig rental and crew, and directional drilling. The time depth curve (Fig. 4.7) assumes that the 9 5/8” casing is set at 400 m. Shifting it down to accommodate directional work will shorten the lower hole section and the length of liner required. The curve shows a total depth of 1000 m; extending the depth to 1200 m will produce a small increase to the total cost. The time required includes rig mobilisation and demobilisation. Consumable costs, such as casing, mud and fuel oil, have been included based on current industry rates. Service costs, such as wireline logging and coring, are also based on current onshore rates, although there is little recent experience in Scotland. Costs include contracting a drilling supervisor and drilling engineer for the duration of the well. Provision has been made in the costs for mud disposal.

Costs have not included well planning in the next stage, for which a provision of at least £50,000 is recommended. Costs have not included provision for site security, a health and safety adviser or the provision of utilities (other than rig fuel), as this is all assumed to be available within the Guardbridge site.

The well costs have been independently reviewed, but nevertheless carry a large uncertainty at this stage, as there are no offset data for drilling performance, no certainty that the high angle well trajectory can be achieved at shallow depths, and no recent experience of drilling near environmentally sensitive areas. Dry hole cost is £900,000 with a P90 – P10 range of £750,000 to £1,100,000. Production well cost is £1,100,000 with a P90 – P10 range of £900,000 to £1,300,000.

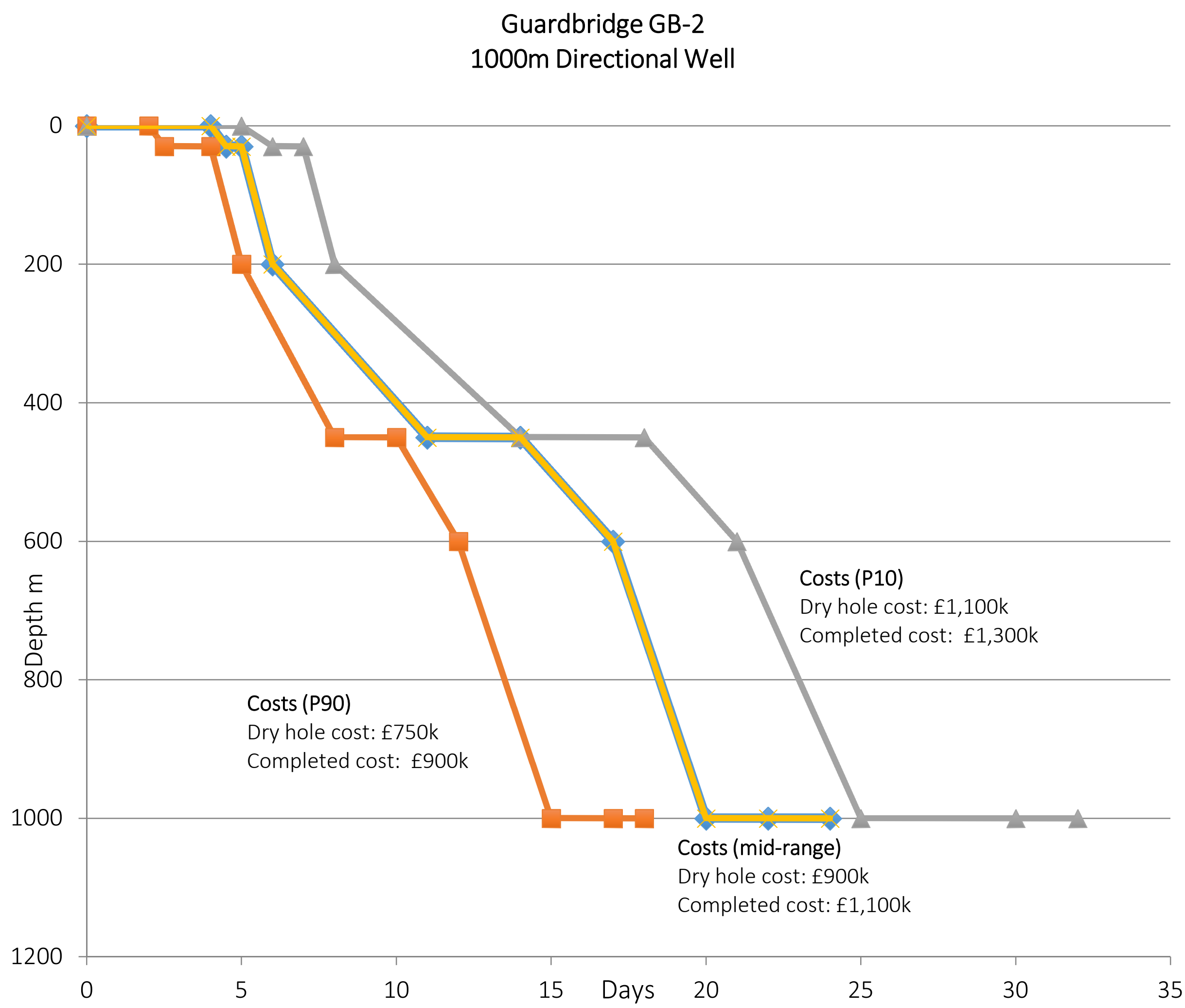


Fig. 4.7 Time-depth curve for well GB-2 with a TD of 1000 m (MD).

4.5 Well risks and other drilling options

An initial risk register (Table 4.1) has been compiled for wells at Guardbridge. All wells have similar risks except GB-2, which has additional risks with the directional drilling and drilling across the Dura Den Fault.

4.5.1 *Lower cost drilling options*

Other drilling options have been reviewed and offer both opportunities and risks. There is an opportunity to progress costing and design of a well similar to GB-2, but using a **minerals slant drilling rig**. This would use a slanted mast in order to eliminate the directional work, and drill a straight slanted hole across the fault and through the target zones. It would eliminate the costs associated with directional drilling and a higher specification rig, but would increase drilling time and is suited to a smaller hole size. The drilling angle is likely to be limited to 20°, so there may be a trajectory that could test the geology and the fault, but it is not possible to drill the higher 60° angle well proposed by GB-2 with a slant rig. It would be possible to recover core for the whole well bore below installing the surface casing (i.e. potentially through the fault zone and target horizons). It would also be possible to acquire some wireline log data, but flow testing may not be possible or would be very restricted by the small hole size. The well could not be completed as a producer. It is anticipated that the costs may be in the region of £250,000 - £450,000. This would need to be further investigated to confirm costs and review associated risks, especially with regard to well control.

Table 4.1. Risks associated with well development.

Risk / Hazard	Consequence	Control Measures
Losses to unconsolidated sands	Formation collapse; loss of mud	Mud additives, offset data research required. Higher risk for GB-2
Hard formations	Vibration and damage to equipment; higher costs	Offset data research required; further design on bits and drill string design
Unconsolidated target zone	Liner will need to be cemented and perforated; Higher costs; formation damage	Formation strength information; offset data research required Potential contingency of cemented liner and perforation.
Caverns	Major losses; stuck pipe	
Water influx	Need heavier mud and fluid; require another string of casing/liner	Confidence in pressures for each formation.
Variable drill rate	Damaged bits and/or lost equipment in hole; higher costs	Bit and drill string design
Drilling through faults	Formation collapse; loss of mud; Difficult to control directional drilling.	Geophysical survey data through the fault and formations. Higher risk for GB-2
Collapse of borehole during testing and/or production	No access to clean out borehole at a later date	Install slotted liner to prevent borehole collapse.

A geotechnical drilling company have proposed drilling a **probe well** of 120 mm diameter to 600 m with air drilling. This would cost less than £100,000, assuming no casings would be required and that drilling could be done with air/foam drilling. This would be a vertical well and would therefore recover less than optimal amounts of data. It may be considered as an option to test the geology on either side of the fault, for example to test the depth to the Ochil Volcanic Formation on the footwall (on-site) or to test the depth to the top of the Knox Pulpit Formation and its thicknesses on the hanging wall (off-site).

4.5.2 ***Other capital costs: water disposal***

In the event of a successful drilling operation with economic flow rates, well GB-2 would be put on long term aquifer production. This requires disposal of the produced water. Three options have been identified:

- *Inject the water back into the aquifer*

This is used in some Danish projects, but it is not the case at Southampton. Injection can maintain aquifer pressure, though there are uncertainties about this until the geology is better understood. Injection water will need to be placed some distance from the producer to prevent early thermal breakthrough of the cooler injected water to the producer. There is greater uncertainty about injection into a well than productivity. The production well can flow with a significant drawdown, but it is more difficult to inject at a significant overpressure. Issues include pump power, formation breakdown (fracturing), and controlling solids in the injected fluid. Injection wells will generally require more frequent intervention and downtime. It may be necessary to have two injection wells to protect against extended inoperation of the producing well. Finally, an injection well will have similar costs to a producer and may require a surface linkage to pumps.

- *Dispose of the water into the sea*

The Southampton scheme disposes of its water to sea. The complexity and feasibility of doing this at Guardbridge depends on water quality, and we assume that the aquifer water will be partly saline, and possibly more concentrated than sea water. If settlement, filtration and dilution can be used to passively treat the water then a settling lagoon equivalent to an Olympic swimming pool would be required to handle 15 l/s of produced water. Environmental concerns are dealt with in Section 11.

- *Clean and recycle the water locally*

The potential for treating the water and recycling it locally is worth investigating. There are water requirements on site and filtration to remove particulates, plus chlorinaton, could be necessary and sufficient treatments to produce potable water, although further desalination treatments are required for conductivities above 5000 μs (pers. commun., Culligan (UK) Ltd). Relevant technology from Culligan (UK) Ltd includes two OSFY 48 or 54 filtration units and a GAC filter that use 10W of power and are therefore inexpensive to run. To de-salinate, vacuum membrane distillation can be integrated into a geothermal energy plant to reduce the operational costs.

Cost estimates for any water treatment, in the absense of a re-injection well, are very uncertain, but in the range of £250,000 to £500,000. Desalination has much higher power costs and creates a residual brine waste, therefore it may be uneconomic and unmanageable at the Guardbridge site.

4.5.3 ***Well life operation and repair costs***

Operating expenditure for the well is limited to the power required to run the ESP. This varies for different scenarios, which are addressed in the economic summary. If used, the passive water treatment plant will have a small operational expenditure for the disposal of solids and it is assumed that this will be part of the overall Guardbridge site costs and an estimate is not provided.

Periodic well interventions to clean out solids and to replace the ESP are very difficult to forecast. Typically, in oil fields with higher temperatures and variable rates, ESP's have lifetimes of 18 months, but a range of 1 month to 20 years. The Guardbridge downhole pump will have relatively benign operating conditions. The only relevant recent experience is for an ESP in a geothermal well in Copenhagen which has operated for 12 years at 60 l/s, and has been replaced primarily due to build-up of dirt in the well over this period. The cost of a well intervention to replace tubing is also difficult to estimate as this requires a fuller understanding of the well design and geology, but one assumption is that it will not require a 100 tonne rig as the tubing can be removed with a light rig or crane.

4.6 Well engineering activities in Phase 2

To progress to a ready-to-drill well, there will be several activities:

1. Conduct a geophysical survey of Guardbridge and surrounding area to attempt to remotely image the aquifer targets and the fault behaviour, and thereby reduce the uncertainty in well trajectory for a deviated GB-2 well.
2. Revise the well trajectory based on increased geological knowledge and choice of drilling rig and review directional drilling constraints.
3. Review available (offset) well data on rate of penetration, drilling fluid and well control to better constrain design and costs.
4. Evaluate whether drilling using a "minerals" slant rig or shallow "probe" boreholes will add value or significantly reduce uncertainty in the final well.
5. Finalise the optimal design for well completion.
6. Produce economic model (costs and re-sale value) for on-site water recycling or disposal-to-sea options, and finalise decisions on water management.
7. Expand and manage the exploration and operation risk register.
8. Complete documentation and licensing applications for DECC, SEPA, SNH, Scottish Water and the Health and Safety Officer.

9. Provide Health and Satefy Executive (HSE) inspectors with detailed drilling plans and risk assessments.
10. Procure rig and other services.

It is estimated that it could take 6 months to reach Stage 7, at which point a case for drilling and rig procurement would be complete. Estimates of time to complete procurement and final well planning is not estimated here.

5. HEAT DEMAND ANALYSIS

Ramboll Energy have assessed the heat demand at Guardbridge (site and town) and the nearby towns of Leuchars and Balmullo using the Scotland Heat Map and future development data provided by the University of St Andrews. This analysis leads to a preliminary network design (Section 6) and an economic model of the potential scheme (Section 7).

The aim of this part of the study was to prepare preliminary district heating network layouts at different scales, based on the demand analysis. These various options provide an indication of the potential annual and peak heating demands that can then be compared against the geothermal heating potential found in Section 4.

5.1 Identifying Potential Demand

The Scotland Heat Map (individual building data) was used to identify areas of heat demand in Guardbridge and the surrounding area (Table. 5.1) and the Fife Development Plan was used to predict future heat demand). From an early stage, it was seen that the only locations within an accessible distance were Guardbridge village, Balmullo and Leuchars. For this study, the town of St Andrews itself was not considered as a potential demand for the system as the closest buildings of large demand, still approximately 6 km away, are University-owned buildings that are currently undergoing connection to a large biomass district heating network. The available heat demand for the towns discussed was extracted and is summarised in Table 5.1.

Table 5.1: Heat Demands in Guardbridge and the nearby towns.

Study Area	Heat Demand (MWh)	Number of Properties
Guardbridge	5452	198
Leuchars	21680	1270
Balmullo	12412	615

1. Guardbridge

The town of Guardbridge itself is relatively small in comparison with the other nearby areas (Table 5.1). It does, however, have the added bonus of being directly beside the proposed energy centre site and so would not need a long section of transmission pipe to be reached. There are also future commercial and residential developments planned around the town and on the former paper mill site where the University of St Andrews Guardbridge Energy Centre is situated.

2. Leuchars

Leuchars is a primarily residential area, with some local shops but no large commercial customers. There is a primary school to the north near an area of ex-council style homes that would offer an area of high heat demand density. One of the most promising aspects of the demand at Leuchars is the military base and its accommodation. This could potentially be treated as a single customer in regards to a heat supply agreement; streamlining connection negotiations and potentially providing a long term, secure source of demand in the network.

3. Balmullo

Balmullo is comprised almost entirely of residential properties in a relatively dense format which is typically good for a district heating network as it can provide high heat demand density which lowers the relative network costs. It is however, a lot further away from the proposed energy centre location, meaning a large amount of distribution pipe would be required for connection. This connection has the added hurdle of having to cross the Edinburgh to Aberdeen railway line, which can be a very expensive procedure as Network Rail have been known to charge in the region of £20,000 - £30,000 p.a. at an interest rate of RPI + 5% for permission to build across one of their lines. Despite their being a small stream and therefore bridge in place already, the works required to install DH pipe here would likely still incur these fees.

Table 5.2 Future development demand estimates.

Future Development Code	Development Type	Land Area (hectares)	Houses	Estimated Demand (MWh)
GUA01	Private Housing	0.2	12	120
GUA02	Private Housing	1.9	69	690
GUA04	Private Housing	3.1	75	750
GUA05	Commercial / Leisure	7.7	NA	4600
LEU01	Private Housing	7.8	125	1250

Table 5.3 Guardbridge paper mill development proposals and estimated heat demands (provided by the University of St Andrews).

Description	Post code	Floor area (m²)	Heat demand (MWh)	Specific demand (kWh/m²)
Phase 1 (2015-2020)				
Offices, Labs, R&D, Workshops 1	Commercial Offices	3,870	488	126
Offices, Labs, R&D, Workshops 2	Commercial Offices	2,460	310	126
Library/ Archive Facility 30km linear of storage	University Building	3,000	324	108
Offices for Library staff	University Building	780	99	127
Offices above Library	University Building	3,200	403	126
Brewery	Retail	220	24	108
Data Centre	Industrial	1,040	225	216
Phase 2 (2015-2025)				
Energy Centre Admin and Visitor centre	University Building	780	99	127
Innovation & Research Centre	Commercial Offices	9,290	1,454	157
Former Boiler House (Listed)	University Building	5,420	850	157
Data Centre Expansion	Commercial Offices	1,160	250	216
Light Industrial 1	Industrial	540	77	143
Light Industrial 2	Industrial	4,705	677	144
Offices, Labs, R&D, Workshops 3	Commercial Offices	2,330	293	126
Offices, Labs, R&D, Workshops 4	Commercial Offices	550	70	128
Offices, Labs, R&D, Workshops 5	Commercial Offices	2,640	333	126
Future Brewery Expansion	Retail	665	72	108
Store	University Building	690	99	143
TOTAL			6,147	

5.2 Future Developments

To maximise the heat demand included in this study and ensure that the network was not just designed for the existing demands, future residential and commercial developments were included in the analysis. There are several areas of land set aside for residential developments around both Guardbridge and Leuchars; details of these were obtained from the Fife Council website and were accurate at the date of initial analysis (August 2015). There is additional development at Guardbridge on the local development plan and this could potentially be connected in the future. The demand estimates for the residential areas were done on the assumption that an average household's heat demand would be 10,000 kWh per year (Table 5.2).

The commercial and leisure space at the site of the old Paper Mill (see Fig. 5.1) was based on data obtained from the University of St Andrews (Table 5.3).

The Guardbridge site heat demands, based on the development strategies of the University of St Andrews, were estimated based on floor area and benchmarks, and more detailed analysis regarding the annual heat demand is recommended. The phasing of this demand was estimated based on the development timescale outlined in Table 5.3.

Table 5.4 Projected development of district heating customers and network expansion

Year	2017	2018	2019	2020	2021	2022	2023
Investment in network in % of maximal	75%	75%	75%	100%	100%	100%	100%
Connection of consumer in % of maximum	30%	50%	75%	90%	100%	100%	100%
Estimated heat delivered per year (MWh/year)	1,844	3,074	4,611	5,533	6,147	6,147	6,147

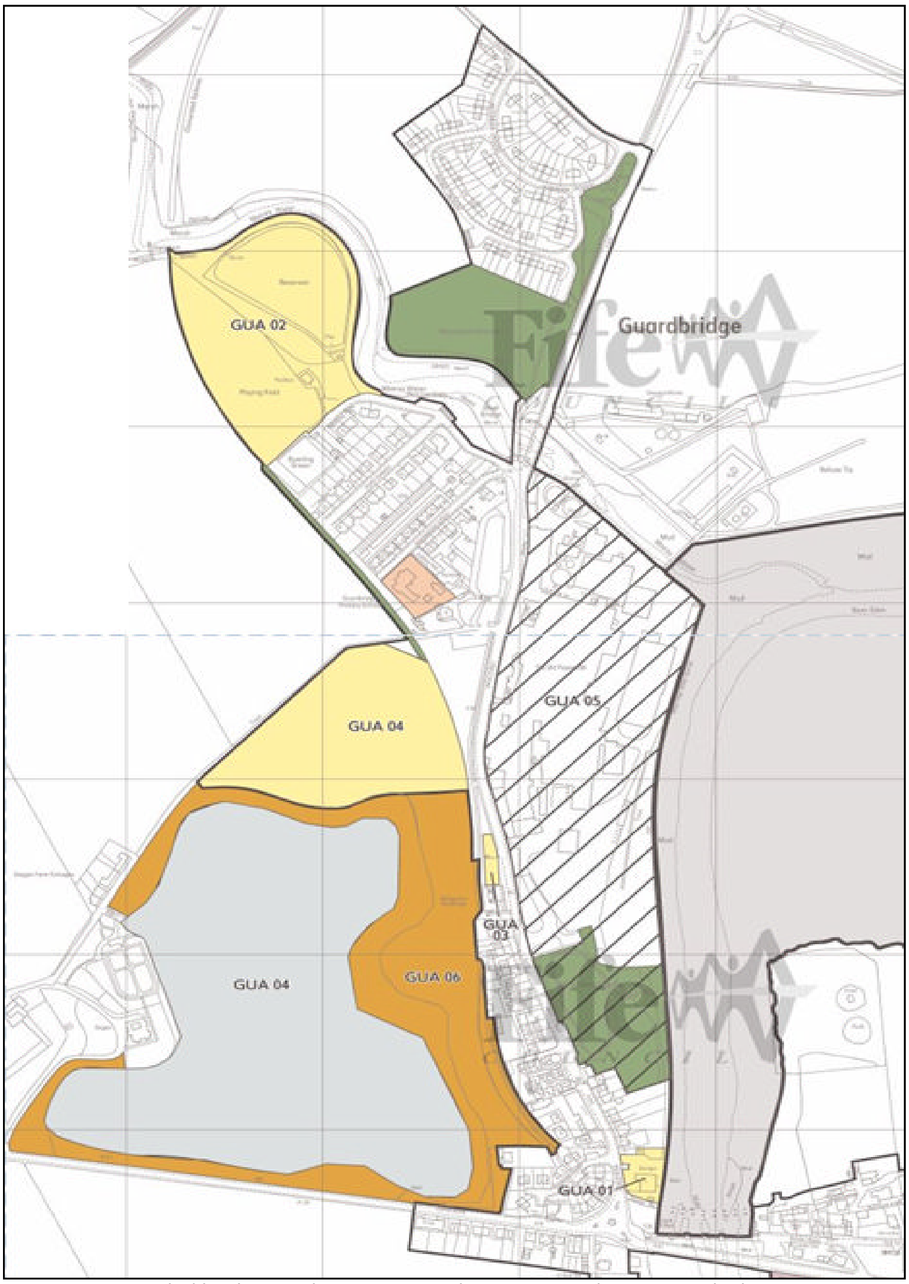


Fig. 5.1 Areas of future development in Guardbridge.

6. PRELIMINARY NETWORK ANALYSIS

6.1 Network Options and Phasing

Once all nearby areas of demand had been identified, a preliminary network layout was drawn in ArcGIS. This network targeted all of the key points of heat demand that had been shown in the analysis of the heat map data and was designed in separate phases to evaluate different scales of network build out. These different phases and areas can be seen below in Fig. 6.1.

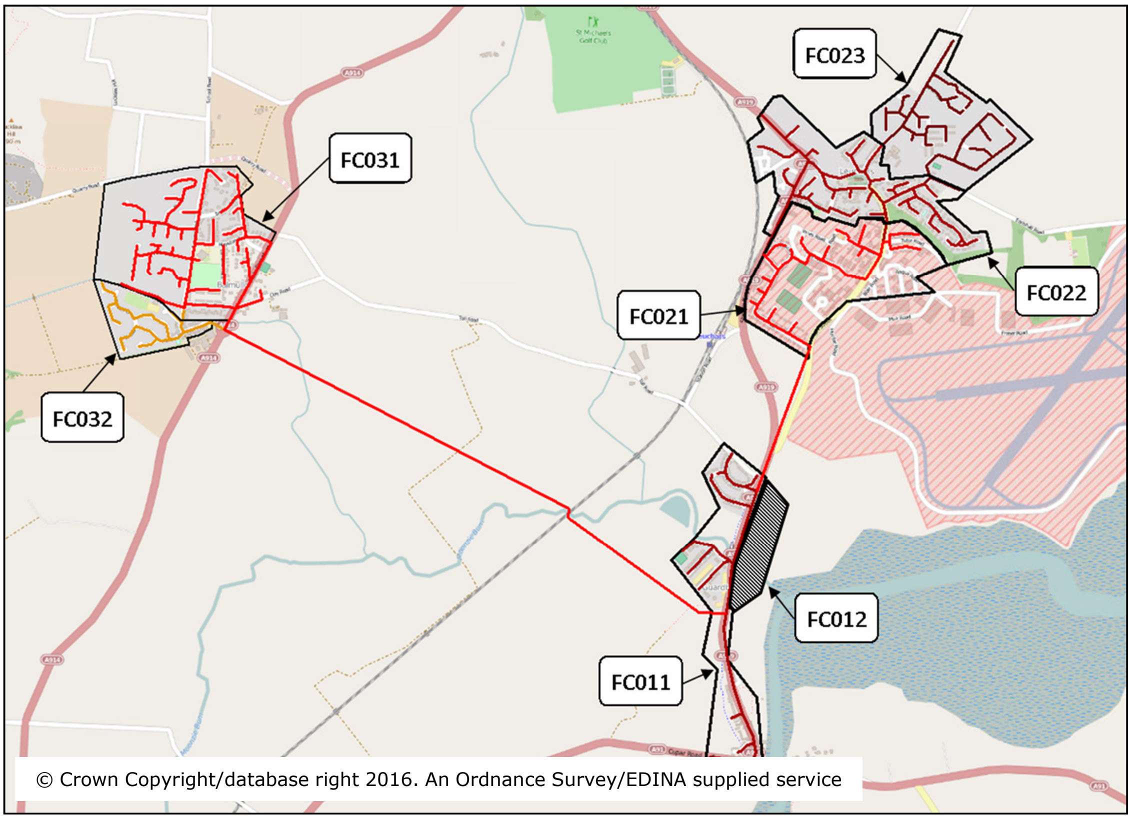


Fig. 6.1 Preliminary and phased network designs for Guardbridge Energy Centre (FC012), Guardbridge village (FC011), Leuchars (FC021, 22, 23) and Balmullo (FC031, 32).

1. FCO11 – Guardbridge

For any build-out scenario, this section of network would likely be the first as it is located next to the site of the Guardbridge Energy Centre. There is a relatively small demand from the residential properties in Guardbridge itself, although there are plans for more housing to be built in the coming years. While this provides a good starting point, a large part of the network demand will come from the future developments at the old paper mill site. This will come in two phases, the first of which is due to be completed in 2017, and a second is scheduled for some time after 2020.

2. FCO12 – Guardbridge Phase 2

This option is the second phase of development at the Guardbridge site. The site will consist mostly of research and commercial space and is estimated to have a total demand of approximately 4,500 MWh. Such a large demand close to the site of heat generation should be an advantage to any network.

3. FCO21 – Leuchars Phase 1

Although supplying Leuchars would require a large amount of connecting pipework, the military housing particularly represents a good source of potential demand and has the advantage of being a single customer which can provide better demand security. An extension into the military base also has the advantage of opening up the network to supply residential demand throughout Leuchars and could help to make full use of the site's geothermal potential.

4. FCO22 – Leuchars Phase 2

The second phase of the Leuchars expansion would reach out in either direction along the main road through the town centre. This has the potential to supply both residential and local commercial customers and as the main connecting pipework is already in place, should help to raise the linear heat density (LHD) of the system as a whole.

5. FCO23 – Leuchars Phase 3

Phase three of the Leuchars expansion spreads out to the northeast to reach the local primary school and an area of council-style blocks of houses that should have a relatively high heat demand density. While there is good demand in this area, it should be noted that the area is less densely packed than the rest of Leuchars and so it may not be economically viable to extend the network this far for a lower than usual demand.

6. FCO31 – Balmullo Phase 1

To the west of Guardbridge is Balmullo, a residential area of moderate density with a significant annual heat demand of approximately 8.5 GWh. However, the connecting pipeline required to get to Balmullo is almost 7 km in length, and although the majority of this could be done through soft ground, the railway line to cross is a major issue as discussed in Section 5.1.

7. FCO32 – Balmullo Phase 2

This second phase in the Balmullo arm of the network is a small extension into an estate of newer build private properties. These are large houses and so the area has a good level of heat demand density, however these figures could be based on benchmarks and in reality newer builds will be more energy efficient and will likely not be willing to pay again for a new source of heating.

6.2 Opportunity Assessment Tool

The District Heating Opportunity Assessment Tool (DHOAT) developed by Ramboll for the Scottish Government was used to analyse the heat map data and preliminary network designs. This tool provides clear indications of what the peak and annual demands would be at each stage of the network's development, as well as providing a preliminary set of key performance indicator (KPI) data, including:

- Total heat demand
- Indicative CAPEX
- Indicative Network OPEX
- Indicative heat sales

The outputs of each scenario can be compared against one another to determine which would be most suitable for the heating network. This decision is based on both the technical figures derived from early modelling, as well as knowledge of the local property types, potential connection issues and any commercial and construction hurdles, such as the railway line that would have to be crossed to reach Balmullo. Another useful KPI to determine the performance of the proposed networks is Linear Heat Density (LHD); this is a ratio of demand to pipe length (MWh/m) and can provide a good early stage indication of whether the network has enough demand to justify the initial capital costs of pipe installation.

6.3 Network Analysis

Table 6.1 presents the initial analysis for the proposed networks. There is a significant variation in the linear heat density between the various options that show quite clearly how additional transmission pipe can significantly decrease the potential of a network. The table also provides approximate estimates of the required primary heat supply capacity which will later be compared against the predicted heating potential of the geothermal resource under Guardbridge, in order to determine what extent of network would be feasible.

Table 6.1 Summary of opportunity assessment results.

Short Name Reference	FC011	FC012	FC021	FC022	FC023	FC031	FC032
Project Name	Guardbridge	Guardbridge Papermill	Leuchars Military	Leuchars Residential 1	Leuchars Residential 2	Balmullo Main	Balmullo Private
Network Length [m]	3648	1210	3144	4235	3950	7998	1410
Total Heat Demand [MWh]	8.0	4.7	3.6	9.8	7.8	8.6	3.8
Peak Demand [MW]	3.7	2.1	1.7	4.5	3.5	3.9	1.7
Primary Supply Asset Capacity [MW]	1.0	0.6	0.4	1.2	0.9	1.0	0.5
No. of Connections	220	0	190	498	381	470	139
Linear Heat Density [MWh/m]	2.19	3.96	1.16	2.31	1.97	1.07	2.68
Revenue	£494 k	£269 k	£204 k	£556 k	£450 k	£476 k	£214 k
Total Capital Cost Lower Range	£5,504 k	£2,237 k	£3,553 k	£7,498 k	£6,155 k	£8,847 k	£2,597 k
Total Capital Cost Upper Range	£9,304 k	£3,820 k	£6,233 k	£12,209 k	£10,272 k	£15,587 k	£4,237 k
Average Heat Selling Price [£/MWh]	62	57	57	57	58	55	56

The LHD for the first Leuchars connection is low in comparison to the two residential extensions (Table 6.1); this is because it bears the burden of the initial transmission pipe to reach Leuchars and so has a large section of network with no customers. However, provided there was enough heat available, this network option would allow the better performing sections to connect, improving the networks overall LHD and so its apparent poor performance should not be a reason to discount it from the study.

Similarly, the two phases of network in Balmullo have very different values for their linear heat density. However in this case, the first network actually reaches most of the demand in Balmullo and so the phase two extension would not provide enough demand to raise this significantly. Coupled with the additional hurdle of negotiating a railway crossing, a heat supply to Balmullo is not considered in any more detail in this report.

7. GEOTHERMAL HEATING POTENTIAL

A traditional heat network has its extent defined either by choice or by available demand, however the extent and capacity of a geothermal-based network is mostly defined by the heating potential of the target resource. This is determined by both the source temperature, which influences the achievable temperature drop, and extraction flow rates from the resource.

7.1 Initial Estimates of Output

Before the geological work had reached its final conclusions, this heating potential was quantified for a wide range of possible values which can be seen in Table 6.1. Due to the initial assumptions around the type of geothermal resource and target depths, it was known that the temperatures found would definitely be below the typical return temperature of a district heating network (DHN), even a low temperature network with a return of 45 °C. This meant that the only possible heating solution would be to utilise a heat pump and to upgrade the geothermal heat to the required network flow temperature. This meant that a temperature drop of 5 °C could be assumed and the potential heat output calculated for a series of flow rates and coefficients of performance (COP's) using the following equation:

$$Q_h = \frac{m \cdot c_p \cdot \Delta T \cdot COP}{COP - 1}$$

where:

$$m = \text{Mass flow rate } (l \approx kg)$$

$$c_p = \text{Specific heat capacity of water } (4.18\ kJkg^{-1}\ K^{-1})$$

$$\Delta T = \text{Temperature drop } (5^oC)$$

It should be noted that although the overall heat production does decrease slightly with a rising COP (Table 7.1), this is because a more efficient heat pump will draw less of its output from electricity. Given a fixed source input, this will therefore reduce the final heat output of the unit. However, the increased COP does reduce the cost of heat by a much more significant margin as can be seen to the bottom of Table 7.1. The range of COP values is based on supplier data (Fig. 7.1).

Table 7.1 Heat pump outputs for various flow rates and COP values, and the indicative cost of heat shown based on 12p/kWh for electricity.

Heat capacity of heat pump based on ΔT of 5 ºC (kW)							
Source Flow Rate (l/s)	COP of Heat Pump						
	3.0	3.5	4.0	4.5	5.0	5.5	6.0
5	157	146	139	134	131	128	125
10	314	293	279	269	261	255	251
15	470	439	418	403	392	383	376
20	627	585	557	537	523	511	502
25	784	732	697	672	653	639	627
30	941	878	836	806	784	766	752
35	1097	1024	975	941	914	894	878
40	1254	1170	1115	1075	1045	1022	1003
Cost of Heat (p/kWh)	4.0	3.4	3.0	2.7	2.4	2.2	2.0

7.2 Final Heat Production Estimates

The final temperature and flow estimates were obtained from Town Rock Energy and were given in the form of one high flow scenario that was more favourable and a low flow scenario with more conservative assumptions (Section 4.1.3). The potential heat outputs[1] of the scenarios were therefore defined as 418 kW for the high flow case and 139 kW for the low flow case.

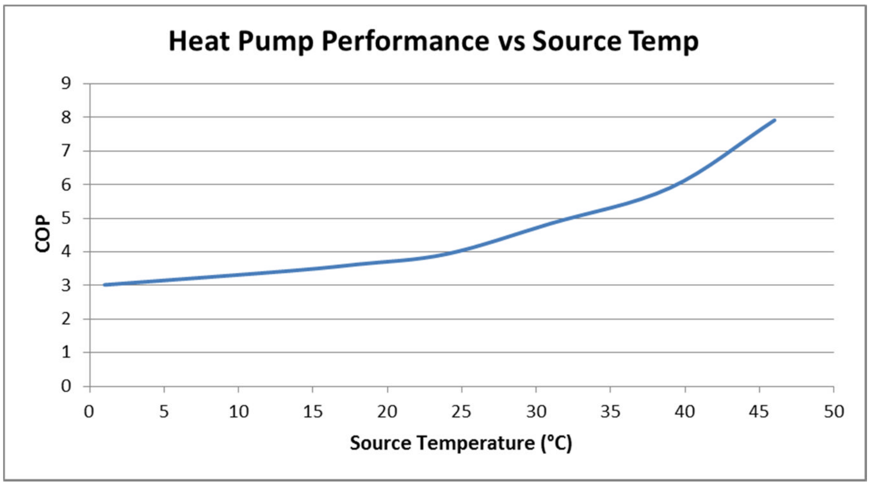


Figure 7.1 GEA heat pump performance against source temperature, delivering at 75 °C.

[1] Based on a source temperature of 25 °C and a COP of 4

8. NETWORK DESIGN

Based on the estimated heat production rates of the target geothermal resource, a heat pump-based system would not be able to provide enough heat for any of the proposed network options outside of the Guardbridge Energy Centre itself. It was therefore decided that the final network design should be focused on supplying heat to the future developments around the Guardbridge site as these are situated close to the proposed well locations and would require the least length of pipe to be connected.

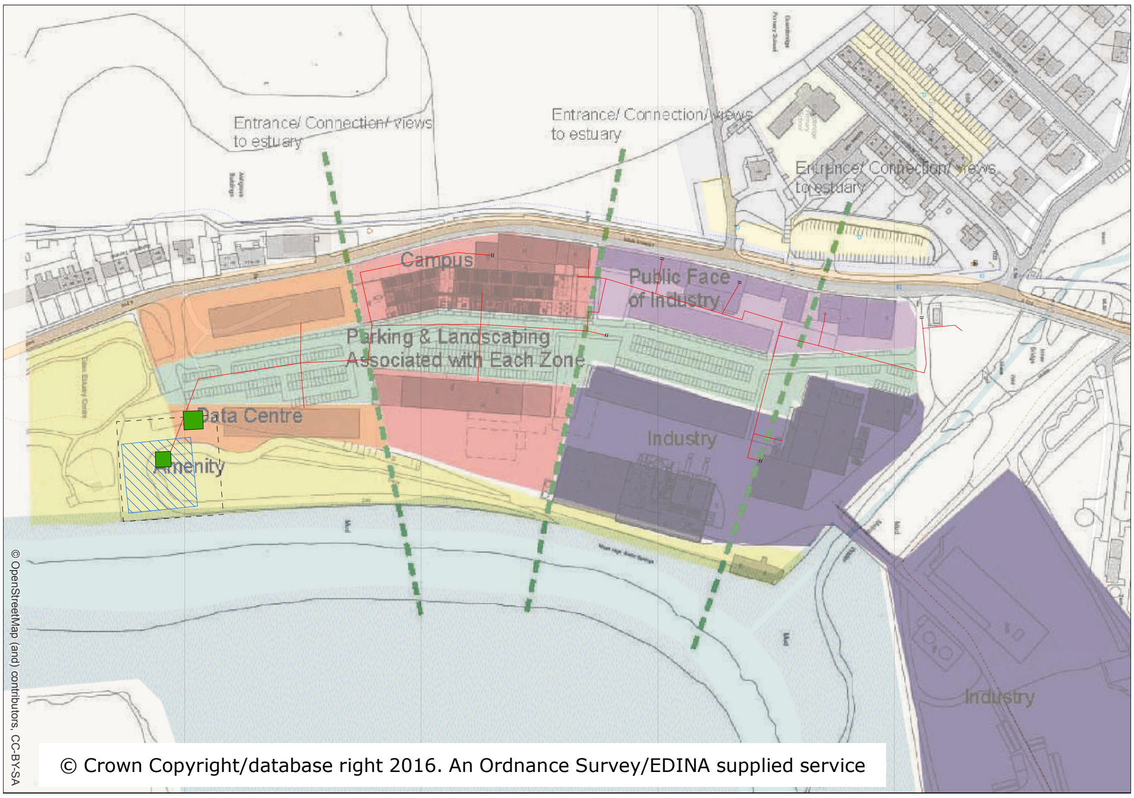


Figure 8.1 Final network design overlain on proposed Guardbridge Energy Centre development plan (the former paper mill site).

The buildings shown in colour in Figure 8.1 are the ones scheduled to be completed in the first development phase and so have been targeted for the first connections. To ensure that the network will remain flexible and able to supply further developments around the site, several capped points have been proposed that will enable other buildings to connect in the future; these are shown in black end points in the plan (Fig. 8.1). It is noted that the network design will require updates based on the timing of building development on the Guardbridge site.

8.1 Well location

This smaller more localised network also benefits from the fact that the preferred well option for the project was proposed to lie inside the Guardbridge site, hence eliminating the need for any long stretches of transmission pipe to get from the well-head to the geothermal energy centre or heat demand.

The geothermal energy centre and production well have been placed a short distance apart to allow for future maintenance of the borehole. Initially it is estimated to require a drilling area of approximately 65 x 65 m, while any subsequent work would require just 45 x 45 m. This smaller maintenance allowance can be seen in Figure 8.1 as the blue hashed square around the production well and the initial drilling footprint is the black square around this. Due to the footprint required for drilling such a deep borehole, all construction around the site would have to wait until after the well had been completed. However, this is the most likeky case as the well production would have to be proved valuable before construction of the geothermal energy centre took place.

9. ENERGY CENTRE DESIGN

The proposed well location is principally selected to target the potential geothermal resource and is located witihn the Guardbridge Energy Centre on the former papermill site. The well head, heat pump and heat station are indicated on Figure 8.1.

The proposed geothermal heat resource will provide baseload supply to the network with back-up capacity provided by the biomass energy centre which is under construction (Fig. 9.1). It may be feasible to extract heat from the return of the district heating main pipes connecting the Guardbridge Energy Centre to the North Haugh in St Andrews. This will depend on a number of factors including:

- The biomass boiler specification for feedwater;
- The temperature specification for the customers on the network;
- The return temperature in the network main.

The development trajectory for the proposed development of the site is indicated in Table 5.2 – 5.4; the heat demand will develop over time and it may be appropriate to delay investment in the geothermal well until baseload demand can be guaranteed. The availability of heat from the biomass energy centre allows the network to be developed in the interim period.

The system indicated in Figure 9.1 shows the heat pump providing baseload and operating in parallel with the thermal store and the back-up heat supply from the biomass energy centre. The heat exchanger between the geothermal energy centre and the network will provide hydraulic separation of the systems and allows the control of system temperatures to the Guardbridge site which will operate on a lower flow and return temperature than the main district heating network.

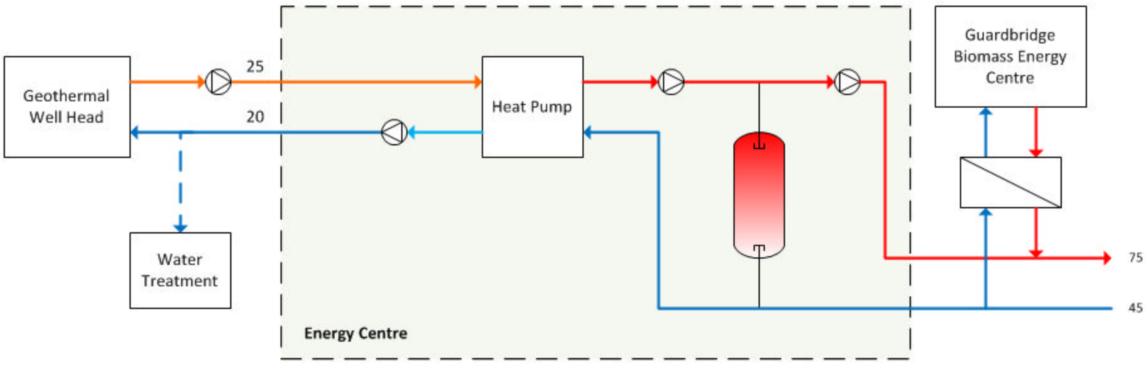


Fig. 9.1 Proposed geothermal energy centre design with backup connection from the Guardbridge Biomass Network.

The geothermal well capacity has been demonstrated above to be limited to approximately 418 kW and the total annual demand on the network in the technical and economic model assumes that the annual load dispatch from the plants will follow the figures indicated in Table 9.1.

Table 9.1: Load dispatch used in energy model

	Capacity (MW)	Percentage of annual load supplied	Demand supplied by plant (MWh/a)	Equivalent full load running hours
Biomass energy centre	2.0	50%	2,867	1,434
Geothermal heat pump	0.42	50%	2,867	6,859

9.1 Combined heating and cooling operation

Figure 9.2 and 9.3 below demonstrate an enhanced system configuration that could be considered at a subsequent stage to provide combined heating and cooling for the site. This would increase the utilisation of the heat pump by operating in combined heating and cooling mode during inter-seasonal periods. The system could also potentially be used to fill separate hot and cold seasonal heat stores. The technical and economic feasibility is not explored further at this stage, but will be worthy of consideration if this project is taken forward.

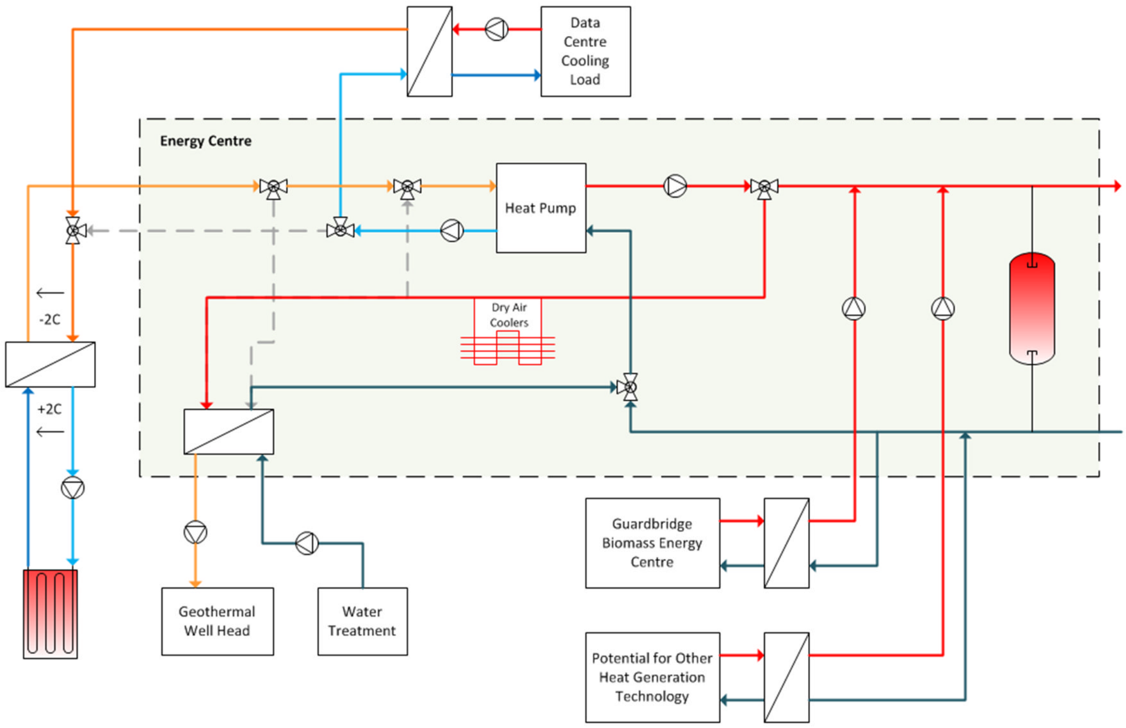


Fig. 9.2 Summer operation for potential seasonal storage.

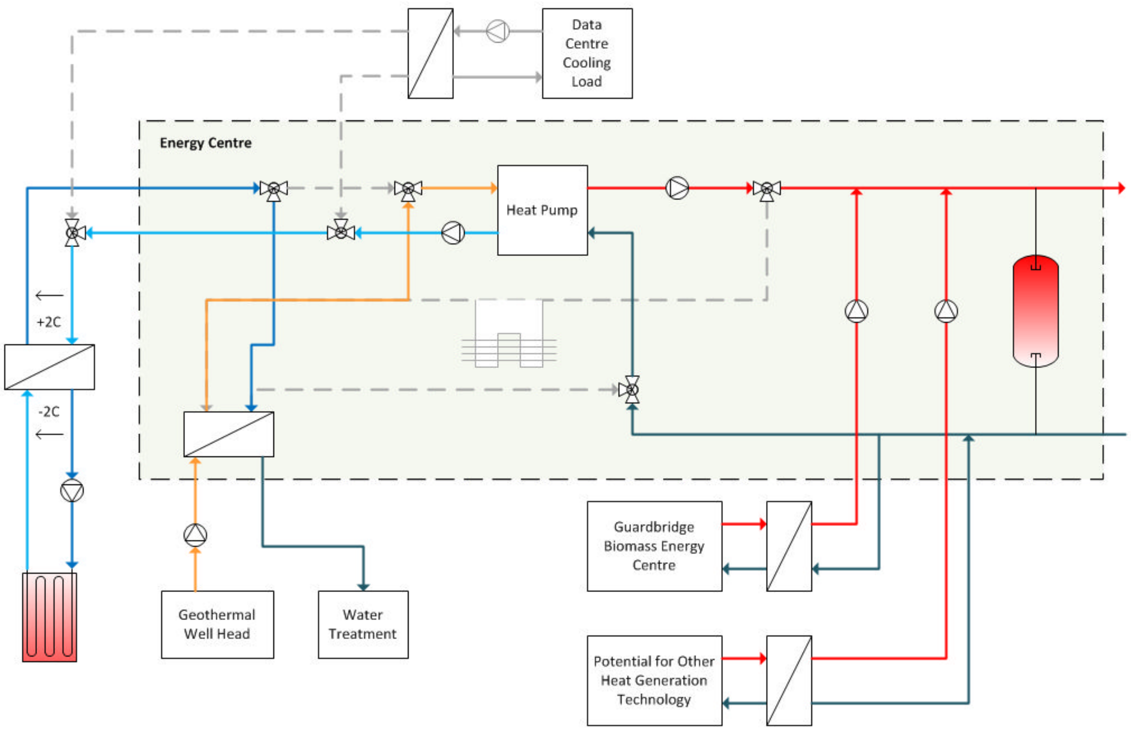


Fig. 9.3 Winter operation for potential seasonal storage.

10. ECONOMIC ANALYSIS

A technical and economic model was developed for the project on the basis of the technical operation and the capital, operational, replacement costs and revenues. The core element in the methodology is an Excel model that offers an overview of the profitability to enable decision making by each of the stakeholders in the project (Appendix B).

The Excel model interacts with important data sources from the remainder of the study, notably the energy demands, predicted system operation and the economic assumptions. These are handled separately in order to make the basic model simple and transparent.

The scenario presented in the economic model is based on a district heating network that connects all proposed buildings on the Guardbridge site. In the short term, the heat supply is assumed to be provided by the biomass energy centre, until sufficient baseload exists to justify investment in the geothermal well and heat pump system. The model assumes the well can sustain 15 l/s of water at a temperature of 25 ºC giving a COP on the heat pump of 4.

Table 10.1 Well, heat pump and energy centre CAPEX.

Item	Central Cost Estimate (15 l/s)	Percentage Variation (±)	
GB-2 well design in next phase	£50,000	50%	
Prepare site, mob rig, drill well GB-2 to 1000 m	£945,000	21%	-13%
Complete well and flow test	£147,000	36%	-5%
Water treatment plant	£375,000	33%	-33%
Water disposal to sea	Incl		
Sub-total well CAPEX	£1,517,000	26%	-17%
Water Source Heat Pump	£183,935	10%	-10%
Thermal Store	£46,166	10%	-10%
Balance of Plant	£100,000	20%	-20%
Building Works	£193,548	10%	-10%
Electricity Grid Connection	£13,620	20%	-20%
Sub-total Heat pump and heat station CAPEX	£537,269	12%	-12%
TOTAL CAPEX	£2,404,269	24%[2]	-17%

[2] Percentage variations for sub-total and totals are weighted average percentage variations based on all reductions being achieved and is a best and worst case.

10.1 CAPEX

The district heating network CAPEX is estimated to be £530,000 for a total pipe network length of approximately 1,200m. A small cost of £40,000 has been included to account for the cost of connecting to the heat transmission main from the biomass energy centre (Table 10.1).

The model includes the cost of heat interface units for all customers but, as discussed below, these costs are assumed to be repaid by customers as a connection charge. This can be presented to customers as an avoided cost for installation of an alternative heating system.

10.2 OPEX and REPEX

The operational costs are estimated to be principally for the power consumption of the heat pump and distribution pumps to the district heating network. This equates to a cost of approximately £280,000 per year. The model assumes a major replacement and clean out of the well after 10 years at a cost of £250,000.

10.3 Revenue

The principal revenues in the model are the RHI and heat sales to consumers. The RHI has been assigned to the project at £50.8/MWh. The heat sales price is a variable and needs to reflect a competitive price against the alternative business case, which would be individual gas boilers or electric heat pumps. The price considered in the base model varies by customer size and is listed in Table 10.2.

Table 10.2 Assumed cost of heat to consumers.

Customer size	Heat sale price	
Heat sales price 0-250 MWh	47	p/kWh
Heat sales price 250-2500 MWh	43	p/kWh
Heat sales price 2500-25000 MWh	42	p/kWh
Heat sales price 25000-250000 MWh	36	p/kWh

10.4 Modelling results

The model generates a 20-year cashflow for the project based on the figures estimated from the analysis described in this report. It calculates the overall economic performance of the project to society in terms of the payback, internal rate of return (IRR), net present value (NPV), and return on investment. This result is useful to optimise the overall system, but the model also presents a transparent economic model that illustrates the benefit to each of the organisations. This is critical in establishing a delivery model that attracts all stakeholders of the system into the project.

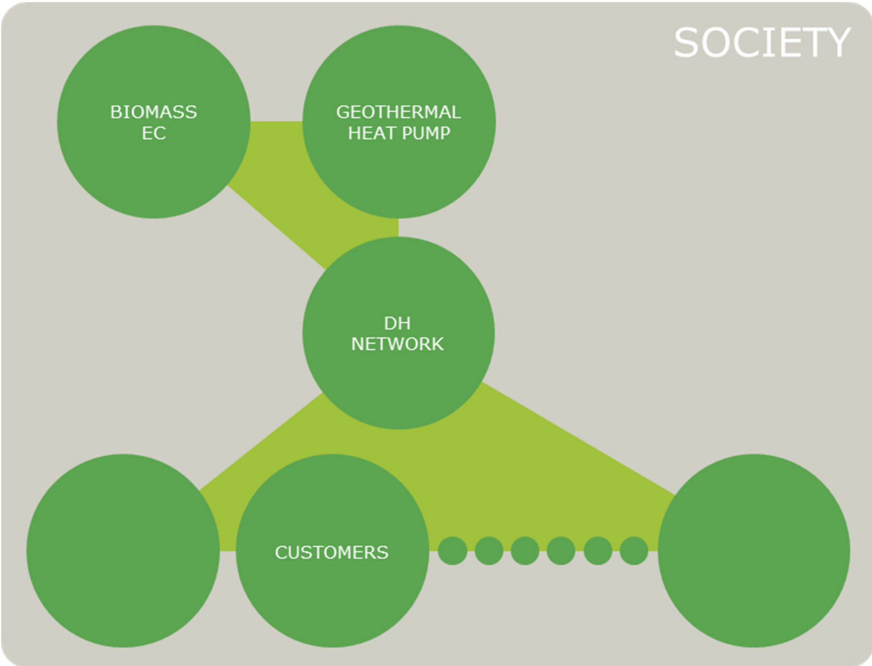


Fig. 10.1 Share of benefit under district heating scenario presented.

The modelling assumptions are presented in a clear and transparent way. The model considers the effect of a range of financing options for the different scenarios, and is run on the basis of the financial parameters for the district heating network shown in Table 10.3. The financing of the geothermal well and energy centre is likely to require specific project investment criteria and for the purposes of this analysis, the NPV and IRR are assumed to provide suitable parameters to assess the viability. The NPV presented in this report for the geothermal well and energy centre is calculated on the basis of a 3%[3] discount rate.

The financial projections are in real terms and do not include inflation. One option will be to finance with the cheapest international 20–year loans on the market (assuming a public sector or state guarantee for the loan). Another option is to assume a private equity financing and a specified return on the invested capital. The model can be adjusted to reflect the revenues from a specified competitive heat price and the result will be an additional short term financing at a specified interest rate.

[3] This is likely to be low if the geothermal well needs to be financed privately

Table 10.3 Financial parameters assumed in the model (related to the DHN).

Parameter	Unit	Assumption
Discount rate	%	3%
Inflation	%	2%
Nominal interest rate, long-term loan	%	5%
Nominal interest rate, short-term credit negative	%	6%
Nominal interest rate, short-term credit positive	%	4%
Depreciation of district heating investments	Years	20

Table 10.4 Key variables affecting performance of the network under conservative expected performance.

VARIABLES	Worst Case		Central Case		Best Case	
	Value	Range/ Units	Value	Range/ Units	Value	Range/ Units
COP	300%		400%		500%	
Well & heat Pump CAPEX	-10%	± 10%	0%	± 10%	-10%	± 10%
Network CAPEX	0%	± 10%	0%	± 10%	-10%	± 10%
Electricity price to large heat pump	11.25	p/kWh	11.25	p/kWh	8	p/kWh
Heat Sales Price to Customers	0%	± 10%	0%	± 10%	15%	± 10%
Heat Price from Biomass EC	41	£/MWh	41	£/MWh	30	£/MWh
Heat Price from Geothermal	50	£/MWh	50	£/MWh	61	£/MWh
Customer connection contribution for Branch & HIU	100%		100%		100%	
Alternative heat supply in absence of district heating	Gas Boiler		Gas Boiler		Heat Pump COP 2.5	
Heat pump operation year	2017		2017		2017	
RHI included	Yes		Yes		Yes	

The biomass energy centre is assumed to supply the back-up and peaking heat capacity to the network and this will come from a heat exchanger connected to a branch off the main network. The cost of heat advised by the University of St

Andrews is 41 p/kWh which covers the cost of an assumed capacity charge of £30,000 per year.

The results for the central scenario (Fig. 10.2) indicate that neither the large heat pump or the district heating network make a positive return if the consumers are supplied with heat at a competitive price compared to the gas boiler alternative. Table 10.5 illustrates how the performance of the network improves under the best case conditions.

Table 10.5 Economic results for scenario modelled on data in Table 10.4.

	NPV k£	IRR (%)	NPV k£	IRR (%)	NPV k£	IRR (%)
Supplier, Surplus heat	-347	3%	50	3%	87	3%
Large heat pump	-555	-3%	-597	-2%	967	10%
District heating company	-359	-7%	-399	-7%	218	10%
Consumers	44		44		1,567	
Total benefit to society	-1,217	-6%	-902	-2%	2,839	28%

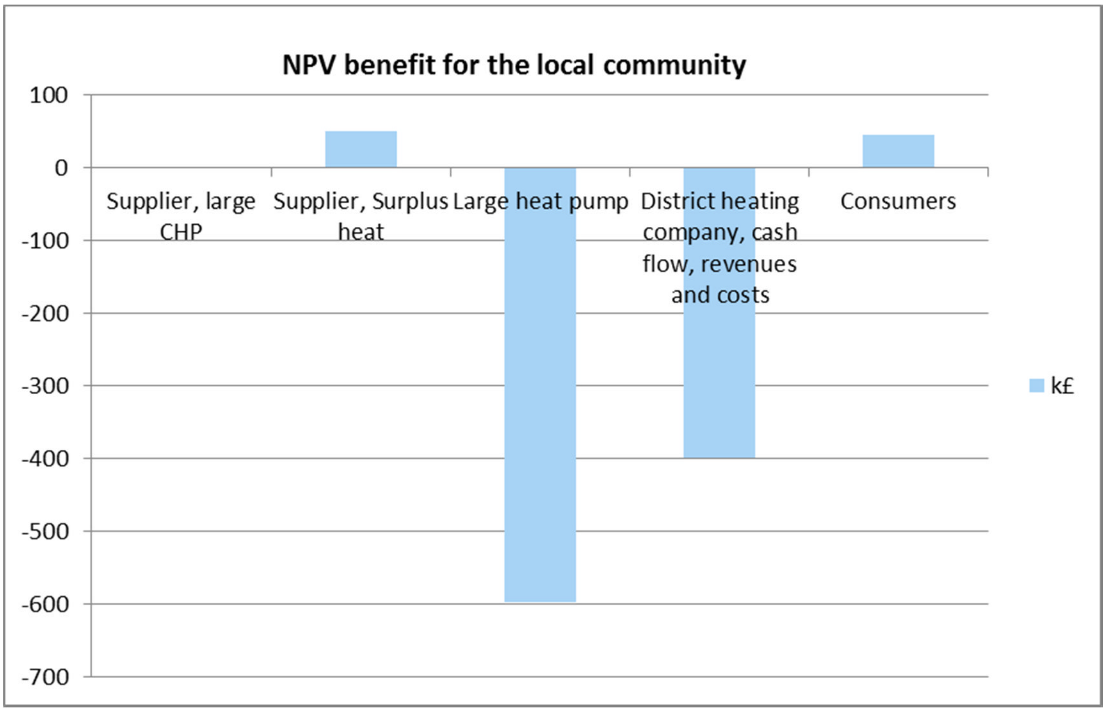


Fig. 10.2 Representation of share of benefit as NPV to each of the stakeholders in the project.

10.4.1 ***Heating Customer Perspective***

The tool presents, for the given solution of heat supply to the Guardbridge site, a comparative assessment of heat price between District Heating and other heat supply options. This demonstrates the relative benefit to customers of connection against the business as usual alternative.

Table 10.6 indicates that each customer, due to their relative size and heat offtake, will have a variable saving from district heating compared to the business as usual alternative. These alternatives are considered to be gas boilers or electric heat pumps. It is notable that small consumers benefit from district heating most under a heat pump alternative and large consumers benefit most under a gas boiler alternative.

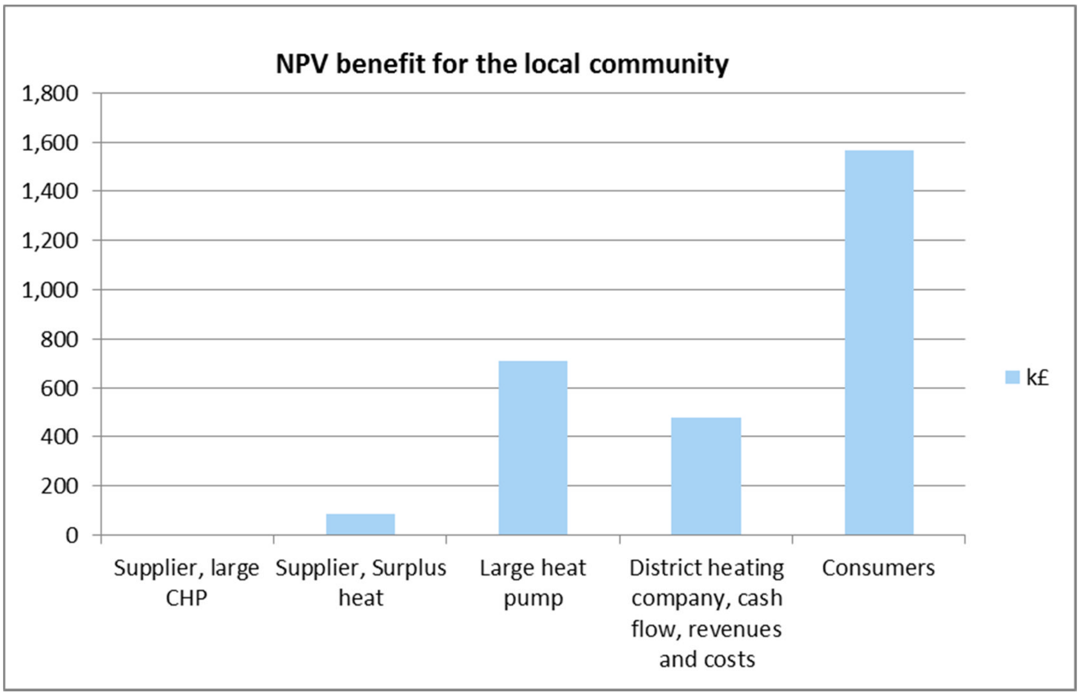


Fig. 10.3 Comparative representation of share of benefit as NPV to each of the stakeholders in the project under best case scenario.

Table 10.6: Comparison between business as usual (BAU) and alternative heating options for consumers compared to 42 p/kWh heat from DH.

Building	Saved cost arising from DH (based on DH price of 42p/kWh)	
	gas boiler alternative	individual heat pump alternative
Offices, Labs, R&D, Workshops 1	2%	12%
Offices, Labs, R&D, Workshops 2	8%	13%
Library/ Archive Facility 30km linear of storage	8%	13%
Offices for Library staff	3%	15%
Offices above Library	4%	13%
Brewery	-23%	25%
Data Centre	9%	10%
Energy Centre Admin and Visitor centre	3%	15%
Innovation & Research Centre	-7%	8%
Former Boiler House (Listed)	-3%	10%
Data Centre Expansion	12%	14%
Light Industrial 1	0%	16%
Light Industrial 2	-1%	11%
Offices, Labs, R&D, Workshops 3	9%	14%
Offices, Labs, R&D, Workshops 4	-1%	16%
Offices, Labs, R&D, Workshops 5	7%	13%
Future Brewery Expansion	-1%	16%
Store	3%	15%

10.4.2 *District Heating Company Perspective*

The district heating operator in this scenario generates an IRR and NPV of 3% hurdle rate. The project under these conditions would not offer a payback after 21 years, despite the residual value of the district heating pipes. Under the best case scenario however, and with a higher heat price to the geothermal well, the network would potentially achieve a positive IRR and NPV which could be commercially viable.

10.4.3 *Biomass energy centre perspective*

Heat from the biomass energy centre will provide the back-up and peaking demand to the network. The cost of heat from this plant will be related principally to the fuel cost to the plant and also to the cost of gas if the demand displaces load on the network. The central estimate of £41/MWh is based on a cost of heat of £20/MWh and the cost or financing a £40k connection from the transmission pipe and a £30k per year share of the operation and maintenance cost. Under this scenario, the energy centre makes a small profit on the sale of heat.

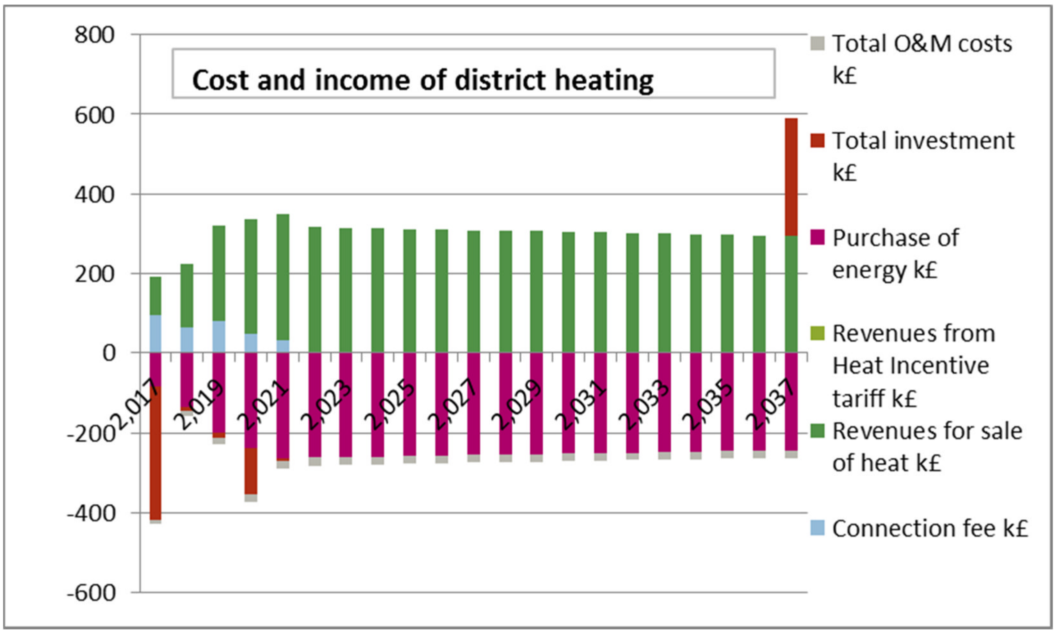


Fig. 10.4 Lifecycle cost for district heating network including residual value at end of period under best case scenario.

10.4.4 *Geothermal well and heat pump perspective*

Under the scenario considered, the geothermal well generates at a peak capacity of 418 kW and can provide approximately 50% of the load on the network. The heat sales price is too low in this scenario to create sufficient margin to make the economic performance attractive. This is principally due to the capital cost of the geothermal well and high operational margin required to pay back the investment. The best case scenario shows that this might achieve a 10% IRR and a positive NPV.

10.5 Carbon emissions

The generation of heat from the geothermal well, using a heat pump to increase the flow temperature, offers potential carbon emissions reductions. These have been compared to a business as usual (BAU) scenario that includes individual gas boilers for each of the customers (Table 10.7). The heat production in the alternative business case requires heat supply of 113,351MWh to be generated by gas boilers. This equates to 28,574 tonnes of carbon emissions. The analysis in the model shows an 84% reduction in carbon emissions under a scenario where biomass boilers and water source heat pumps supply the majority of the demand through a local district heating network.

The carbon emissions factor associated with the biomass boilers is 7 $kgCO_2/kWh_{th}$ based on the carbon emissions of different fuels, provided by the Biomass Energy Centre website (www.biomassenergy.org.uk). The carbon emissions factor associated with the electricity grid is 300 $kgCO_2/kWh$ and this is predicted to reduce over the lifecycle of the project. The reduction in grid emissions intensity has been included in the model based on Figure 5.2 in the DECC report enetitled *Updated Energy & Emissions Projections - November 2015*.

Under the scenario modelled for this study, the biomass boilers contribute approximately 50% of the heat demand (up to 3 MWh per year) and the heat pumps contribute the remaining 50% of the demand. The biomass boilers have low carbon emissions associated with them and the majority of the predicted CO_2 emissions are associated with the carbon emissions intensity of the grid supplying the geothermal well pumps and the heat pump. This equates to 4,677 tonnes over the 20-year lifetime of the model. These are significantly lower than the alternative scenario where heating is supplied from gas boilers. Furthermore, the carbon intensity of the electricity grid is reducing with the build out of low carbon energy generation systems connecting to the electricity grid. About 58% (13,878 tonnes CO2/kWh saved relative to the BAU) of the carbon emissions reduction is attributed to the heat supplied from the biomass plant and 9,812 tonnes CO2/kWh saved relative to the BAU (42%) is attributed to the geothermal well pumps and the heat pumps.

Table 10.7 Carbon emissions reductions from district heating compared to individual gas boilers.

20 Year Lifecycle Carbon Emissions Reduction		
Total CO_2 emission district heating	4,677	Tonnes
Total CO_2 emission baseline	28,574	Tonnes
Saved CO_2 emission district heating compared to baseline	23,987	Tonnes

The value of this carbon saving is not included in the model since it does not currently represent a cost to the University, however it could be considered to represent an additional saving compared to the BAU alternative. The following items are excluded from the above calculation of carbon emissions:

- the embodied carbon emissions associated with the manufacturing and transport of the buildings, plant and equipment;
- any carbon emissions associated with degassing the well which are expected to be negligible;
- carbon emissions associated with the produciton, drying and transport of biomass to the biomass boiler plant.

10.6 Sensitivity

As noted previously the model calculates the overall economic performance of the project to society in terms of the payback, IRR, NPV and return on investment. This economic benefit to society is shared between the stakeholders. The economic performance in the model is sensitive to a series of variables. Some of these represent internal transactions within the model and do not affect the economic performance for the whole society, but do influence the share of the benefit between individual customers.

The following parameters are critical in the model for distributing the benefits among the various organisations but do not affect the overall project economics:

- Heat Price from Geothermal
- Heat Sales Price to Customers
- Customer connection contribution for Branch & HIU
- Cost of heat from biomass Energy Centre

The following parameters were varied and the influence on the overall economic performance or the benefit to individual organisations is discussed.

1. Variation in source temperature and Heat Pump COP

An increase in the temperature that the resource could sustainably deliver would enhance the COP of the heat pump. Varying the COP from 4 to 5 improves the project IRR from 3% to 4% and the IRR for the energy centre from 0% to 1%.

2. Well and heat pump capital costs

The CAPEX for the well and heat pump has a significant effect. A 10% reduction on the CAPEX improves the project IRR from 3% to 5% and the IRR for the energy centre from 0% to 3%. A 10% increase on the CAPEX reduces the project IRR from 3% to 1% and the IRR for the energy centre from 0% to -3%.

3. Timing of heat pump operation

The uncertain development of the heat load at the site, and the opportunity to supply heat from the biomass energy centre, means that it may be prudent to wait until the load is guaranteed before investing in the geothermal well. This is feasible and does not affect the overall cost assumptions, but delays the investment in the network. Establishing the network from 2017 and investing in the heat pump in 2020 improves the IRR from 3% to 4%.

4. Renewable heat incentive (RHI)

The RHI is vital to the economic viability of the project and will allow the demonstration of the project with the expectation that the lessons learnt from installing deep geothermal wells can be shared, and the costs and risks of installation can be reduced generally. The removal of the RHI from the modelling assumptions reduces the overall IRR to society from 3% to -2%.

10.7 Summary of Economic Analysis

Based on the economic analysis, the project can demonstrate reasonable performance under a scenario where the anticipated geothermal resource can yield the predicted performance and the costs and risks are well managed. The model clearly shows, however, that the economic performance of the scheme is sensitive to a number of factors and it is the combination of sensitivities that need to be considered. Tables 10.4 and 10.5 indicate the relative performance under the baseline set of assumptions and a reasonable best case assumption.

The results in Table 10.5 indicate that the central estimate for the project delivers a -2% IRR and the district heating company generates a negative IRR and NPV. The geothermal system will deliver a negative IRR and NPV over a 20-year lifetime. This result will make the geothermal system, with the inherent risk of not reaching the required permeability in the rock, a poor investment prospect. It is notable, however, that there are a number of sensitivities that could improve the model performance and this scenario has been presented below.

The results presented as the best case scenario in Table 10.5 show a significantly more attractive project. The assumptions made in this scenario are not unreasonable, but will require further investigation, although they do not provide a margin for uncertainty and risk. The cashflow for this scenario is shown in Figure 10.5.

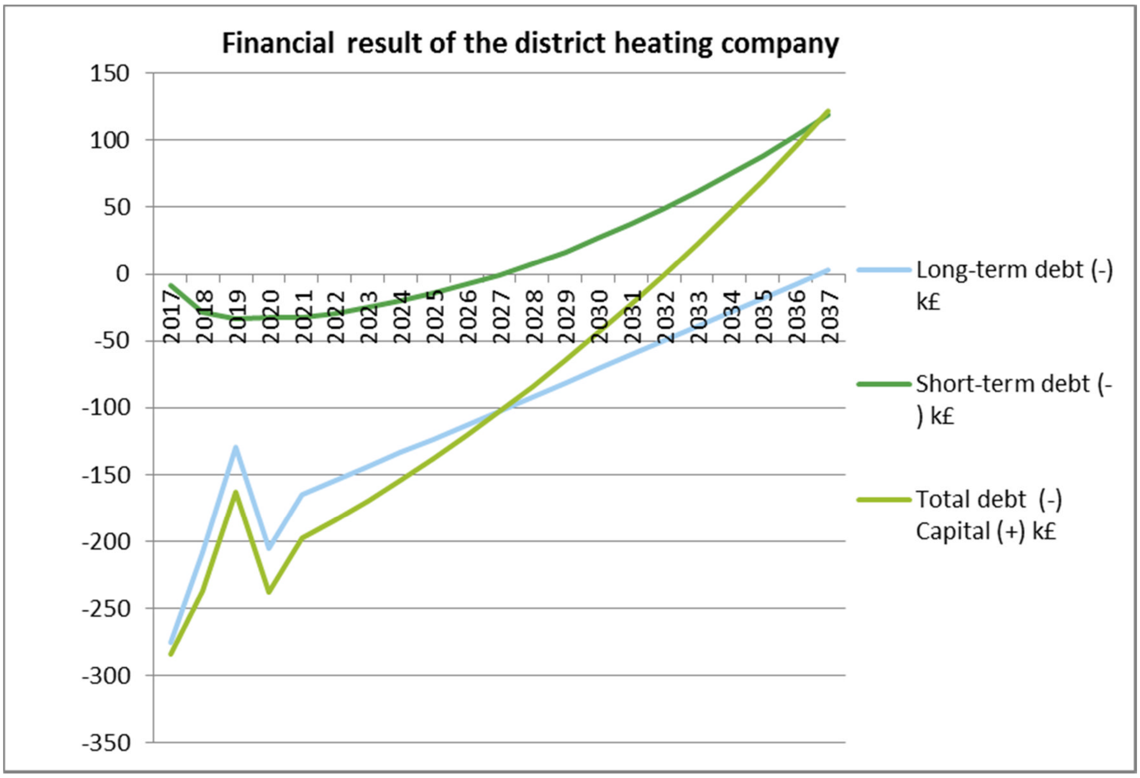


Fig. 10.5 Financial result for the investment in the district heating network only.

11. REGULATORY CONSIDERATIONS

11.1 Introduction to the environmental concerns

The key environmental concerns about the development and production of a geothermal well are related to the exploitation of a groundwater resource, the impact of exploration and operation on the surrounding environment in the sensitive and protected area of the Eden Estuary, and what happens to the geothermal water after the heat is extracted. The Eden Estuary is part of the *Firth of Tay and Eden Estuary* Special Area of Conservation (SAC) site and the estuaries represent high quality Annex 1 estuarine habitats (Regulation 33(2) of the Conservation Regulations). The Eden Estuary is a Site of Special Scientific Interest and a Local Nature Reserve. The Guardbridge Energy Centre sits between the Eden River and the Motray Water, directly adjacent to the tidal flats of the upper estuary (Fig. 11.1). Species include tidal reed beds of *Phragmites australis* and mudflats contain mud-dwelling invertebrates, such as the amphipod *Corophium volutator*, the mud snail *Hydrobia ulvae* and ragworm *Hediste diversicolor*; these species support the over-wintering waders and wildfowl. Saltmarsh communities include *Juncus gerardii*, *Scirpus spp*. and *Puccinellia spp.* with *Festuca spp.* (Bates et al.,

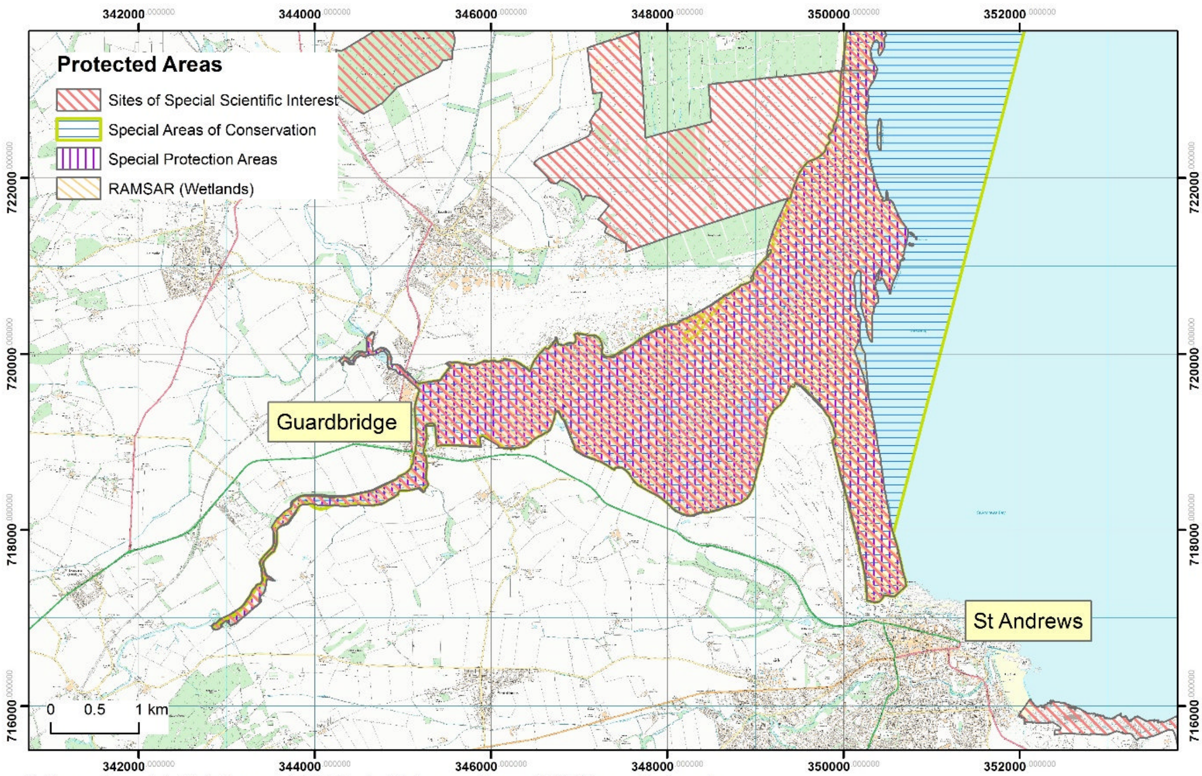


Fig. 13. Guardbridge is sited next to the Eden Estuary which has SSSI, SPA, SAC and Ramsar status. Data are gathered from Scottish Natural Heritage.

2002). Sparse beds of eelgrass *Zostera angustifolia* can also be found to some extent in both estuaries and reefs of the mussel *Mytilus edulis* are common on the intertidal banks of the main Eden Estuary channel (Bates et al., 2002). The reefs support the common starfish *Asterias rubensin*. The mussel reefs are confined to the intertidal muddy areas where they support ephemeral green algae, such as *Enteromorpha sp.* that extend as thick mats during the summer months. Several species listed in Annex II of the Habitats and Species Directive also occur regularly in the Firth of Tay and Eden Estuary SAC. There is a non-breeding population of grey seals (*Halichoerus grypus*) that travel up and down the estuary, and otters *Lutra lutra* occur on the River Eden above Guardbridge. The intertidal sediment flats (to mean low water springs) are an existing Ramsar site and classified SPA for overwintering wildfowl and waders, as well as for the marsh harrier *Circus aeruginosus* and little tern *Sterna albifrons* (Bates et al., 2002).

As a tidal estuary, the salinity changes from upstream of Guardbridge to the estuary mouth and over tidal and seasonal cycles. Salinities approaching 0 psu are associated with the River Eden flows upstream of Guardbrdige, but can reach 25 psu within the mudflats at and around Guardbridge, or as high as 46 psu in salt flats (Spears et al., 2008). Any water disposal to sea as part of the water geothermal water management would need to accommodate these spatially and temporally varying salinities.

11.2 Regulatory requirements

The regulatory issues involve licensing to abstract a groundwater resource and for disposal to sea, and also adherence to EC habitat regulations. The relevant regulatory authorities and organisations involved are the Scottish Environmental Protection Agency (SEPA), Fife Council, Scottish Natural Heritage, and Scottish Water. Exploration for, and disposal of, water is regulated under the Water Environment (Controlled Activities) Scotland Regulations (CAR) 2011 (amended 2013). Geothermal exploration and abstraction will require registration and a Simple License (for a borehole > 200 m deep and abstracting 50 – 2000 m^3/d). Disposal to sea will require a Complex License that covers surface water run-off during drilling and inorganic and thermal effluents as point source pollutants (> 100m^3/d). Applications to SEPA for registration and authorisation will also need to follow guidance covered in WAT-RM-05: Regulation of Trade Effluent Discharges to Surface Waters or WAT-RM-06: Regulation of Trade Effluent Discharges to Groundwater.

Table 11.1 Identified environmental issues associated with a hot saline aquifer geothermal project at Guardbridge.

Factors to consider	Likely effects	Potential impacts
Drill site preparation – creating stable and flat surface for drill rig.	Soil and rock removal (limited quantities)	Particulate material could enter surface waterways
Drilling Well GB-2 – dry hole scenario	Elevated noise and dust levels for 15 – 30 days. Use of drilling muds adds particulate matter to site.	Potential disturbance to breeding birds. Particulate material could enter surface waterways and groundwater.
Drilling Well GB-2 – production hole scenario	Same effects	Same impacts
Pump flow rate tests and initial water extraction	No effects identified for pump tests. Extracted water needs to be stored and tested for water chemistry and particulate content. If suitable, water would be diluted to ambient Eden Estuary salinities.	Test water could cause deterioration to habitats if not de-mineralised and of too high/low temperature (greater than 3 °C difference) (short lived).
Demobilisation of rigs and drilling support	Elevated noise and dust levels for 1-2 days.	Minimal impact of materials entering surface waterways (and short lived).
slump risk from the drilling		
Development of well to production phase	Dust as site is renovated for operational phase.	Minimal impact of materials entering surface waterways (and short lived).
Construction of geothermal energy centre	Elevated noise and dust levels. Some influx of pollutents into soils.	Minimal impact of materials entering surface waterways (and short lived).
Construction of heating network	Some noise and dust creation.	Minimal impact of materials entering surface waterways (and short lived).
Operation of geothermal well – water treatment and recycling option	Water treated through filtration systems and recycled on-site. Negligible losses.	Minimal to no impact.
Operation of geothermal well – partial recycling, and some disposal to sea. Water settling and dilution, filtration and possible treatments depending on chemistry of water.	Water equilibrated to estuary temperatures in settling pond, and diluted to estuary salinities.	Commercial effluent could cause deterioration to habitats if not de-mineralised or if affecting natural salinities – cumulative effect to be considered once volumes are better understood.

Article 6(3) of the EC Habitats Directive is adhered to in Scotland through a Habitat Regulations Appraisal (HRA) which is required for any plan or project which is likely to have a significant or uncertain effect on the integrity of a site (HRA of Plans: Guidance for Plan-making bodies in Scotland, 2015). Since the Eden Estuary is a Special Area of Conservation (SAC), a Special Protected Area (SPA) and a Ramsar site, as well as a Site of Special Scientific Interest (Fig. 11.1), any developments surrounding such sites and involving noise, disruption of soils and rock, or disposal of water and sediments to sea requires careful consideration, licensing and permissions.

For this report, an outline of the recommended developments for a geothermal well as proposed in Section 4 has been discussed with the Scottish Environmental Protection Agency and Scottish Natural Heritage, in order to identify the main concerns and the appropriate licensing and legislative requirements. As part of this report, the potential factors, effects and impacts associated with a Guardbridge geothermal project, were it to go ahead, have been listed in Table 11.1, and this would need to be formalised for the screening stage of a Habitat Regulations Appraisal.

11.3 Requirements for Phase 2 Stage

SNH (Gavin Johnson of SNH Cupar) were contacted as part of this feasibility study and this section summarises their response. If the project is to go to the stage of exploratory test drilling, or is to be completed as a production well, it is very likely to that an Environmental Impact Assessment and an Environmental Statement from the developer will be required before any work on site can commence, due to adjacency of the Guardbridge site to the Eden estuary SPA; the final decision for this lies with Fife Council. The project is "*likely to have a significant effect*" which will need to be evaluated. Regardless of whether an EIA is required, a legislative assessment will be required by the developer in the form of a *Report to Inform an Appropriate Assessment*.

As part of the planning applications for the biomass plant (Fife Council 14/02334/EIA), Environmental Statements were submitted which have been reviewed as part of this report. These extensive documents provide an existing baseline for any future Environmental Statements and are therefore very useful in identifying the risks to the sensitive surrounding areas. SNH have noted that while the investigation into the environmental impacts of exploration and operation of a geothermal well will be a function of the scale of the proposed construction, operation, waste water disposal and heat storage if developed, the project will be viewed in conjunction with other ongoing operations at Guardbridge.

SNH was advised by their ornithologist that construction and operational (direct and indirect) impacts will need to be assessed. For Phase 2, detailed plans will be required to provide more information on partial and/or full disposal-to-sea, the disposal location and the nature of what is being disposed in terms of salinity, pH, and elemental geochemistry, as well as the temperature, volume, flow rate of the water. An assessment of any disposal will need to evaluate the impact upon the biota within the intertidal sediments or the eelgrass growth, i.e. the prey/food base for the qualifying bird interests of the SSSI, SPA and Ramsar sites. To evaluate the impact of the disposal-to-sea option on the biota, particularly the saltmarsh, SNH will require values for the maximum disposal quantities and frequencies, along with the Eden River river flow data and estuarine flushing.

Given the potential for the project to progress with a recommendation for some or all of the geothermal water to be disposed to sea, a competent authority (SNH or Fife Council with the latter's consultation) will need to complete an Appropriate Assessment. Phase 2 of the Guardbridge Geothermal Project will need to consider all of the conservation objectives below:

1. Population of the species as a viable component of the site
2. Distribution of the species within site
3. Distribution and extent of habitats supporting the species
4. Structure, function and supporting processes of habitats supporting the species
5. No significant disturbance of the species

Table 11.2 summarises some of the environmental and legislative guidance that will be relevant to developing Phase 2 of the project.

Table 11.2 Review of environmental and legislative guidance relevant to local authorities.

EC	UK / Scottish	Main requirements	Regulator
EC Directive 2001/42/EC: 'Strategic Environmental Assessment' and EC Directive (85/337/EEC) Environmental Impact Assessment: Assessment of the effects of certain public and private projects on the environment environmental legislation and permitting (consenting) requirements	Environmental Impact Assessment (Scotland) Regulations 2011	Requires certain developments to prepare an Environmental Statement as part of the planning approval process.	Local Authorities
	Town and Country Planning (Scotland) Act 1997 as amended by the Planning etc (Scotland) Act 2006 Planning and Compensation Act 1991 (as amended) ;and Environment Act 1995 (as amended)	Planning permission is likely to be required for deep geothermal developments. Consider: noise from drilling, seismic activity, waterway pollutions and subsidence. Also consider site impact, including transport, hydrology, ecology, visual/ landscape impact and decommissioning.	Local authorities
	Environmental Protection Act 1990, Part III	Statutory nuisance (i.e. non-regulated activities), noise, odour, antisocial behaviour, etc	Local authorities (though planning conditions)
	The Air Quality Standards (Scotland) Regulations 2007. Scottish Statutory Instrument No. 182; The Air Quality Standards (Scotland) Regulations 2010. Air Quality (Scotland) Regulations 2000. Scottish Statutory Instrument No. 97. The Air Quality (Scotland) Amendment Regulations 2002	Set emission limits for certain substances and requires authorities to take action where quality parameters are exceeded.	Local authorities, SEPA
	Control of Pollution Act 1974, Part III; Environmental Protection Act 1990, Part III; and Environment Act 1995, Part V.	Requires local authorities to take action where noise limits are exceeded.	Local authorities (though planning conditions)
	The Management of Extractive Waste (Scotland) Regulations 2010		Local Authorities

12. STAKE HOLDER MANAGEMENT

The University of St Andrews has been in discussion with the Guardbridge community for the last 3 years over all developments at the site. It has developed a full community engagement programme through 2015/16 relating to its Biomass Energy Centre construction project. Communications and engagement meetings have been held on Community Council meeting nights at Balmullo and Guardbridge, with additional drop in meetings at St Andrews and Guardbridge. Separate councillor briefings have also been held. Discussions have involved Councillor Tim Brett and a new forum involving the community and the University is being developed to manage and improve the flow of information between all parties. As a part of ongoing discussion, the community have been made aware of the Geothermal Energy Feasibility Study and its remit. Given the timing of the study and that final conclusions were drawn in January 2016, no specific presentation has been made to the Guardbridge community in regards the final recommendations of the feasibility study. This can now go ahead with the conclusion of the study and submission of the report to the Scottish Government, and the University is in contact with Cllr Brett and the Community Council of Guardbridge to organise a presentation.

The viability of extending the geothermal district heating infrastructure beyond the borders of the Guardbridge industrial site appears to be uneconomic at this time, and so the decision was made to confine community discussions for the geothermal project to heat users in the Guardbridge site. The university and Eden Brewery are both supportive of the potential for renewable heat energy from this project.

13. CONCLUSIONS

The following conclusions arise from the Guardbridge geothermal heat feasibility project in terms of estimated water temperatures and flow rates, well design options, investigation of the scale of potential district heating network, the CAPEX, OPEX and REPEX for exploration and DHN network development, and construction of economic models accounting for all predicted financial costs and the revenue from the sale of the heat.

C1. At the end of this study, which corresponds to the Catalyst Stage following the Low Carbon Infrastucture Transition programme project stages, the evaluation has shown a potentially viable scheme both technically and economically, though at low return in the base case.

C2. The geology beneath the Guardbridge site is suitable for geothermal exploration and using available rock characteristics data and the presented geological model, two flow rates are predicted that are 1) low and 2) reasonable-high estimates associated with temperatures in the range of 23 – 27 ^{o}C.

C3. Several well designs have been considered, all technically achievable, and a single well design has been taken forward for the economic evaluation. The well is estimated to be capable of delivering water at about 25 ^{o}C with a flow rate of 15 litres/second, producing 418 kw of heat(± 10%).

C4. The economic model developed for this project predicts that the district heating network option that is economic involves the Guardbridge site only, and that with a flow rate of 15 l/s, 50% of the district heat required at Guardbridge could be supplied by geothermal sources.

C5. The combination of geological thickness and depth uncertainty, plus the very large range in porosity and permeability observed at any depth in offset wells, results in an order of magnitude uncertainty in flow rates and corresponding heat potential. Higher temperatures due to deeper aquifers, or higher flow rates due to better permeability, will both significantly improve the project's performance economically.

C6. It is expected that some uncertainty in aquifer depth and thickness can be reduced through undertaking low cost geophysical surveys, which have not been possible within this study. The primary geological uncertainty of flow rate can only be constrained and reduced by drilling and testing the aquifer flow rate.

C7. Developing a wider DHN to surrounding communities is not economic based on the current network density or considering the known future potential network developments. A single well at the relatively low temperature estimated here will not provide sufficient heat to expand the network beyond the Guardbridge site.

C8. The geothermal heat project benefits from the proximity to the biomass energy centre and combining the two systems could provide a dual heating and cooling system, and an opportunity to conduct research on integrating different low carbon energy systems.

C9. The location of the Guardbridge project is ideal for producing critical data on the most productive Hot Sedimentary Aquifers in the Central Belt of Scotland and could be used to significantly de-risk other HSA geothermal exploration projects.

C10. Recycling some of the geothermal water to potable standards for use or sale is worthy of further investigation. A flow rate of 15 l/s equates to 54 m^3/h which is a considerable volume to process, but filtering and chlorination may be low energy and sufficient methods to produce potable water. Waters in excess of 5000 μs would need additional treatment at a cost of 5 – 10kW/m^3per day. The Guardbridge site could provide the research focus to advance technology in this area and develop the on-site and off-site customer base, but some disposal-to-sea of treated water will be required, dependent on flow rates and the volume of water that can be utilised or sold.

C11. Any progress to an exploration phase will most likely require an Environmental Impact Statement and assessments from SNH and Fife Council, along with planning permission approval and abstraction licenses from Fife Council and SEPA, and permission to drill under any land that is not part of the Guardbridge site.

14. RECOMMENDATIONS AND NEXT STEPS

The following recommendations arise from the feasibility project in terms of developing a strategy for Phase 2 and for progressing the Guardbridge project to the drilling stage. Although some indicative costs are provided for a non-invasive geophysical survey, the EIA (if required) and the initial drilling stages, the detailed scope of the project and specific costs associated with any engineering, stakeholder engagement, financing and project management are not included, as they are somewhat contingent on findings from the environmental assessments and initial drilling results.

R1. The Guardbridge HSA Geothermal Heat Project should be progressed to the next stage which is a *Development in the Low Carbon Infrastructure Transition Programme* project. In this stage, the final business case, financing options and business organisation will be developed. Whilst it has marginal economic value at the end of the *Catalyst* stage, there are opportunities in the *Development* stage to increase the project value through proving better aquifer delivery, through cost reduction particularly with respect to locally sourced electricity pricing for the heat pumps, and optimising the business model and financing options with regard to different stakeholders. The *Development* stage will probably include drilling to reduce uncertainty before committing to the capital investment required for the District Heating Network. Alternatively, the DHN may be built with initial heat source from the biomass plant assuming a later progression once the geothermal heat source is available.

R2. Reduction of aquifer uncertainties requires a drilling programme. This is seen as a three-stage programme: build a detailed case for drilling, including decisions on whether test boreholes are going to add value; procure a rig and complete detailed well planning and permitting; drill and test the well.

To progress the first phase, which is the decision to drill a well, there will be several activities:

- Conduct a non-invasive geophysical survey of Guardbridge and surrounding area to attempt to remotely image the aquifer targets and the fault geometry and thickness and reduce the uncertainty in well trajectory for a deviated GB-2 well. Costs in the range of £10,000 will provide these geophysical data. About three months would be required to acquire, process and interpret the data.

- At the same time, planning applications will be submitted to Fife Council outlining the construction and completion phases of the geothermal exploration. It is most likely that an Environment Impact Assessment will be required before the project can progress to the site preparation and drilling stage. Relevant license applications to SNH, Fife Council, as well as SEPA, will be completed and, if deemed necessary, an Environmental Impact Assessment will be completed. The time frame for this is a minimum of 3 months at an approximate cost of about £30,000, but could take longer and be more costly if more baseline data are required by Fife Council and/or SNH. Permission to drill must be negotiated with any landowners affected.

- Revise the well trajectory based on increased geological knowledge and understanding of directional drilling constraints at shallow depths.
- Review available (offset) well data on rate of penetration, drilling fluid and well control to better constrain design and costs.
- Decide whether a "minerals" slant or a geotechnical rig and an exploration borehole will add value or significantly reduce uncertainty in the final well. This will depend on whether these lower cost approaches can provide meaningful data on aquifer flow potential.
- If an exploration well is decided, a rig will be procured, the well plan completed and drilling undertaken assuming all permissions are in place. Work to reach this stage will require at least six months and planning costs in the range £30,000 to £50,000. A test bore will cost in the range £100,000 to £450,000 depending on the objectives of the well and necessary rig type.
- Evaluate the results of the exploration well, including flow rate tests and water chemistry, revise the final well design and optimse the well completion design.

Note that the procurement and detailed well planning and permitting time for the final production well has not been estimated as it would require a formal organisational structure. This would form part of the activities of the project in its Demonstrator Stage.

R3. The consortium involved in this feasibility report should be responsible for Phase 2 work and the creation of a suitable ESCO or similar organisation would occur at an early stage to take the project forward to execution and operation, if decided.

R4. An economic model comparing re-injection costs (requiring a second well but extending the life of the resource) against on-site water recycling (costs and re-sale value) or disposal-to-sea (environmental concerns) is required in Phase 2, in order to finalise decisions on water management. Currently, the estimated water treatment costs include development of a settling pond, and the CAPEX and OPEX for filtration and chlorination (£350,000). Any disposal to sea of treated water has to be approved by the competent authorities. Higher salinity water may require reverse osmosis (vacuum membrane) treatment with higher operational costs and results in a residual brine waste.

R5. Optimise CAPEX and OPEX assumptions in the project. In particular, the best case in this study has highlighted the value added by accessing lower electricity prices throughout the project's life for heat pumps. This may be possible through accessing the generating capacity of the Guardbridge project as new energy sources come on line.

R6. Revision of the DHN design to accommodate any changes in the customer base at Guardbridge would be made after a decision to complete the well is made, and at that point more detailed plans and costings will be produced.

R7. Some of the geothermal water can be recycled on site to potable standards as part of an geothermal heat and water recycling project, developing a circular economy model for the resource. The on-site demand and re-sale potential should be evaluated as part of Phase 2. The innovation centre and University is well placed to advance research in streamlined water management for geothermal projects.

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15.2 Guidance and regulatory documents

Regulatory Guidance: Geothermal Heat in Scotland

http://www.gov.scot/Resource/0049/00493200.pdf

The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (as amended) http://www.sepa.org.uk/regulations/water/

Scottish National Planning Framework 3

http://www.gov.scot/Publications/2014/06/3539/downloads
http://www.gov.scot/Resource/0049/00493200.pdf

Conservation (Natural Habitats, &c.) Regulations 1994, as amended – guidance

http://www.snh.gov.uk/protecting-scotlands-nature/protected-areas/international-designations/natura-sites/

Natura sites and the Habitats Regulations - How to consider proposals affecting Special Areas of Conservation and Special Protection Areas in Scotland

http://www.snh.gov.uk/publications-data-and-research/publications/search-the-catalogue/publication-detail/?id=1364

DECC Report: Updated Energy and Emissions Projects 2015

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/501292/eepReport2015_160205.pdf

Biomass Energy Centre

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