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UK Low Enthalpy Geothermal Resources: the Cheshire Basin

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ABSTRACT

Geothermal energy extraction from low enthalpy resources within the UK is something of a hot topic; whilst the UK has only one working geothermal system (Southampton), there is scope for geothermal energy to make a more significant contribution to the UK energy portfolio. A major assessment of UK geothermal resources was undertaken by the British Geological Survey, between 1976 and 1986. This identified low enthalpy resources associated with Permian and younger sedimentary basins. The total resource held within these basins was estimated at 292.6 EJ (Rollin et al., 1995); many times larger than the entire UK heating demand. More recently, work undertaken by Newcastle University and Durham University included drilling two new geothermal exploration wells at Science Central, Newcastle-Upon-Tyne and Eastgate, County Durham respectively. These wells both penetrate Carboniferous strata, and in the latter case the Devonian Weardale Granite. No wells have been drilled to further assess the potential held within Mesozoic basins.

One of the prospective areas for development of geothermal energy is the Cheshire Basin. A recent Deep Geothermal Review Study of the UK (Atkins, 2013) highlighted the basin as being a probable heat generating reserve. It comprises Permo-Triassic sediments extending to at least 4.5km depth, underlain for the most part by Carboniferous strata. Temperatures are estimated to reach 100°C at 4.5km.

The underlying Carboniferous Coal Measures and Namurian shales are gas and oil prone respectively and in the linked East Irish Sea Basin to the north-west have sourced the petroleum deposits found in both Morecambe Bay and Liverpool Bay. Shows of petroleum are common in the Cheshire Basin but only two sub-commercial deposits have been found. We also know from many wells in the East Irish Sea Basin that the strata are permeable, capable of flowing at rates of at least 10 liters sec^{-1}; a figure comparable with that achieved by the UK's single low enthalpy geothermal scheme in Southampton. The Cheshire Permo-Triassic rocks are also excellent aquifers and have been exploited extensively, particularly in the Peckforton Hills.

The combination of permeable formations at temperatures of around 100ºC at 4.5km coupled with the possibility of producing associated hydrocarbons (which could be an additional high-value energy stream) could provide a viable new domestic energy resource. The Cheshire Basin also lies close to the large population centres of Manchester and Liverpool both of which could benefit substantially from low carbon, district heating schemes.

1. INTRODUCTION

The UK's 2008 Climate Change Act committed the country to reduce greenhouse gas emissions by at least 80% (compared with the 1990 base level) by 2050. This is a huge undertaking that requires radical change to the way in which the country uses energy and captures emissions. No single technology can deliver this target (IPCC, 2014) but the use of low enthalpy geothermal energy could make a significant contribution. Improvements in drilling technology and development of binary cycle power generation plants has increased global geothermal availability (Bertani, 2009) by improving the economic case for the exploitation of low enthalpy resources (i.e. those having temperatures of up to 150ºC). Geothermal prospecting requires searching for suitable thicknesses of permeable formations at sufficient depth to yield suitable temperatures. The possibly of developing geothermal energy is enhanced in areas where the geothermal gradient is elevated. In general terms groundwater within basin systems needs to be tapped at depths of 1 to 1.5km or 2 to 3 km to produce water temperatures in excess of 40°C and 60°C respectively. Finding strata that are sufficiently permeable to support the abstraction necessary to supply the intended amount of heat can be a major risk for geothermal projects. To that end, reservoir analogues from the petroleum industry can add some confidence; for example permeability data from sandstone and chalk intervals which are significant oil and gas producers in the East Midlands (Hirst et al, 2014) and the North Sea (Adams et al., 2010) can be used as analogues in the areas considered for geothermal exploration but for which few data exist.

Geothermal wells that penetrate basins containing groundwater in permeable formations that is heated by conductive heat flow are termed low enthalpy systems. Given sufficient temperatures, these systems can be used to provide direct heat or used in conjunction with heat pumps or combined heat and power (as at Southampton in the Wessex Basin). Geothermal reservoirs offer a finite resource but typically have life-spans of decades, the limiting factor being the low thermal conductivity of rocks which limits the rate of heat transfer back into the reservoir (Downing and Gray, 1986). However wells can be re-commissioned after a rest period and deviated or horizontal wells can be drilled from the same well pad and well head. The six factors that influence well longevity were identified by Hanano et al. (1990) as well output, well density, injection strategy, reservoir pressure, initial temperature and reservoir permeability. Longevity of geothermal plants on a scale of decades has been demonstrated at the Lardarello field in Italy since 1913 (Henley and Ellis, 1983) and the Wairakei field in New Zealand since 1958 (Henley and Stewart, 1983). In addition, the

Geyser geothermal field of California has been operating commercially since 1960. Productivity peaked in 1989 before slowly declining due to overdevelopment. Injection of municipal effluent water since 1998 has stabilised the output of the field, renewing the lifespan of the field for at least another 20 years (Sanyal & Enedy, 2011). It is generally accepted that if possible it is better to re-inject spent geothermal waters (which will still have residual thermal value) to prolong the life of the reservoir and maintain reservoir pressure.

Though low-enthalpy in nature, the UK's geothermal resource base is very large. Busby (2010) estimated the technically usable heat resource in the four deep sedimentary basins in the UK and two in Northern Ireland to be approximately $300x10^{18}$ Joules. This value is based upon extraction of hot water alone. The magnitude of the resource becomes apparent when you consider that the current UK yearly energy 'bill' amounts to approximately $8x10^{18}$ Joules of which 45% is used for domestic, industrial and service sector heating (DECC, 2013), and so if this resource play could be developed commercially, the size of the resource would not limit growth.

In this paper we examine both the potential and challenges of developing one of the UK's largest geothermal resources, the Cheshire Basin. The Cheshire Basin occurs in the NW Midlands of England (Figure 1). The cities of Liverpool and Manchester are on its northern margin and the total population of this region is about 5 million and the area just over $4000km^2$ (Greater Manchester, Merseyside, Cheshire; UK Office for National Statistics).

2. OUTLINE GEOLOGY OF THE CHESHIRE BASIN

The Cheshire Basin covers an area in excess of $3500km^2$ (Figure 1) and is approximately 100km in length and around 55km in width.

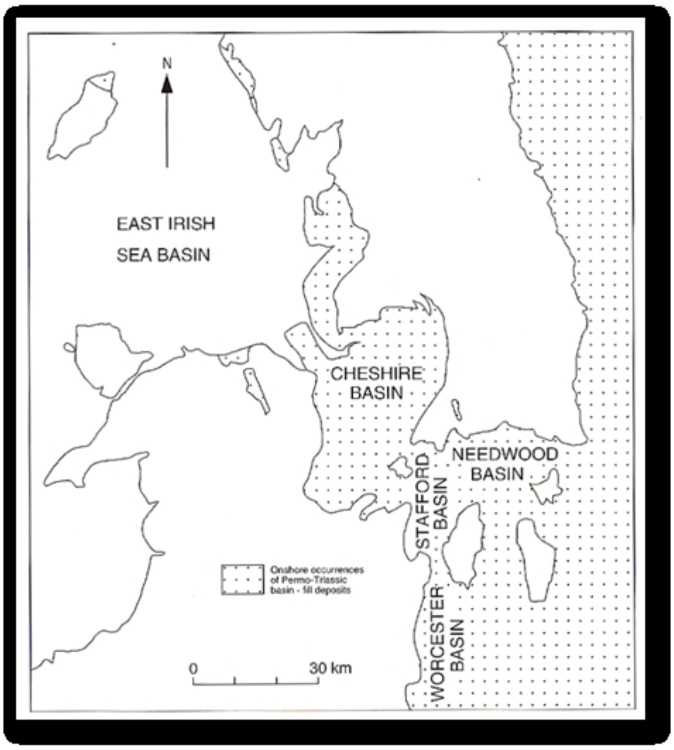

Figure 1: Location and Extent of the Cheshire Basin (after Plant et al., 1999)

The basin forms part of a complex Permo-Triassic rift structure bounded by faults and filled with thick (> 4500m) deposits of Triassic strata (Sherwood Sandstone Group, SSG) and Permian strata (Collyhurst Sandstone, CS) sediments (Figures 2 and 3).

Most of the basin is overlain by the Mercia Mudstone Group (MMG) and it is bounded by the Carboniferous rocks of the Pennines to the east and of the Wrexham Coalfield to the west. These sediments rest unconformably upon folded Carboniferous strata that in turn lie on a Lower Palaeozoic basement. The Cheshire Basin hosts a range of resources including vast reserves of halite that helped to establish the UK chemical industry during the 19th century. The basin contains large aquifers that are important for potable water supply and contains industrial aggregate minerals and sedimentary-copper type base metal mineralisation formerly worked at Alderley Edge, Grinshill and in the Peckforton Hills from the Bronze Age until the early 20th century. The Cheshire Basin has been of interest for hydrocarbon exploration since the late 1970s (Mikkelsen and Floodpage, 1997), though as yet few wells have been drilled. Oil seeps are more commonly found around the periphery of the basin, within Carboniferous strata. However, discoveries within the basin have been reported. Figure 6 shows the hydrocarbon shows and discoveries that have been made across the Cheshire Basin to date. Whilst not over-run with discoveries, Mikkelsen and Floodpage (1997) concede that ignoring the hydrocarbon potential of the basin is unwise given the sparse dataset available for the area.

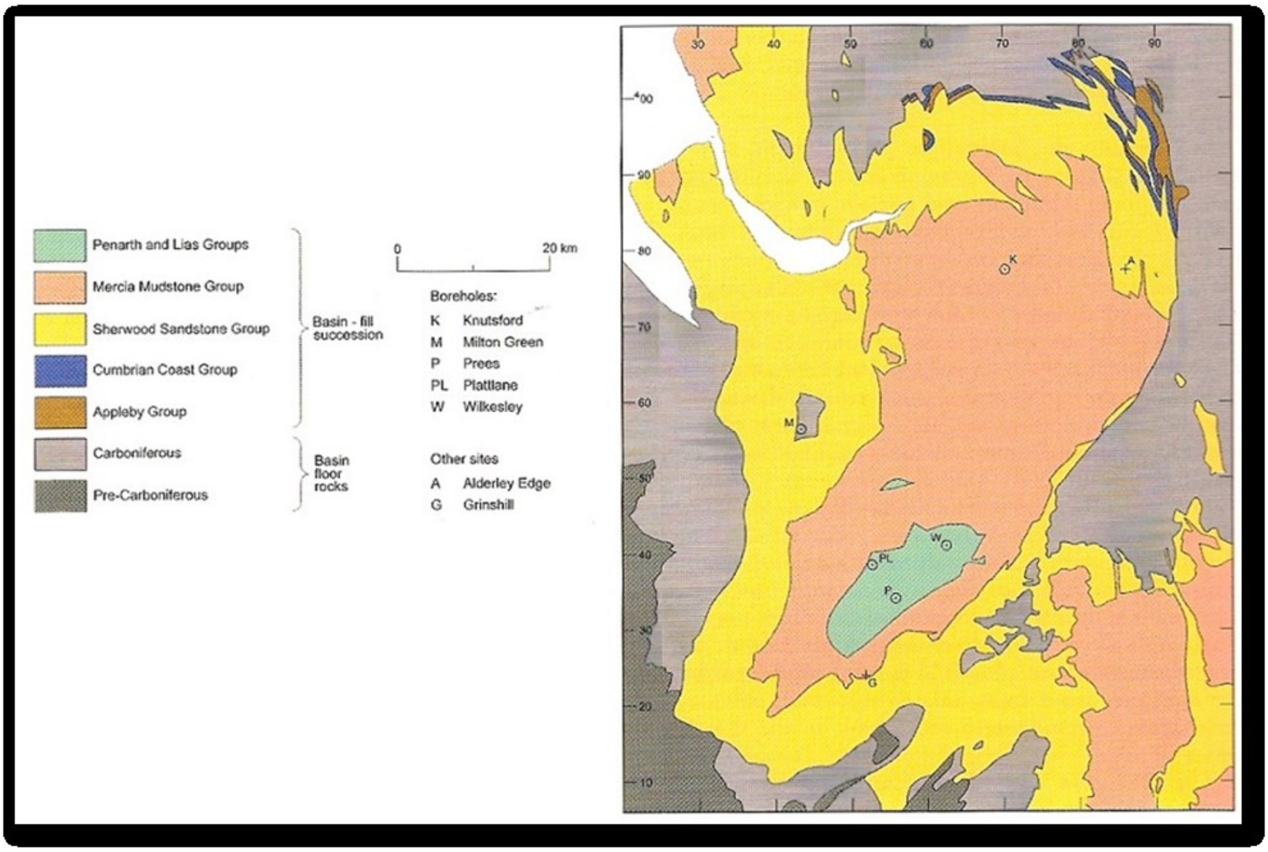

Figure 2: Geological Map of the Cheshire Basin (after Plant et al., 1999)

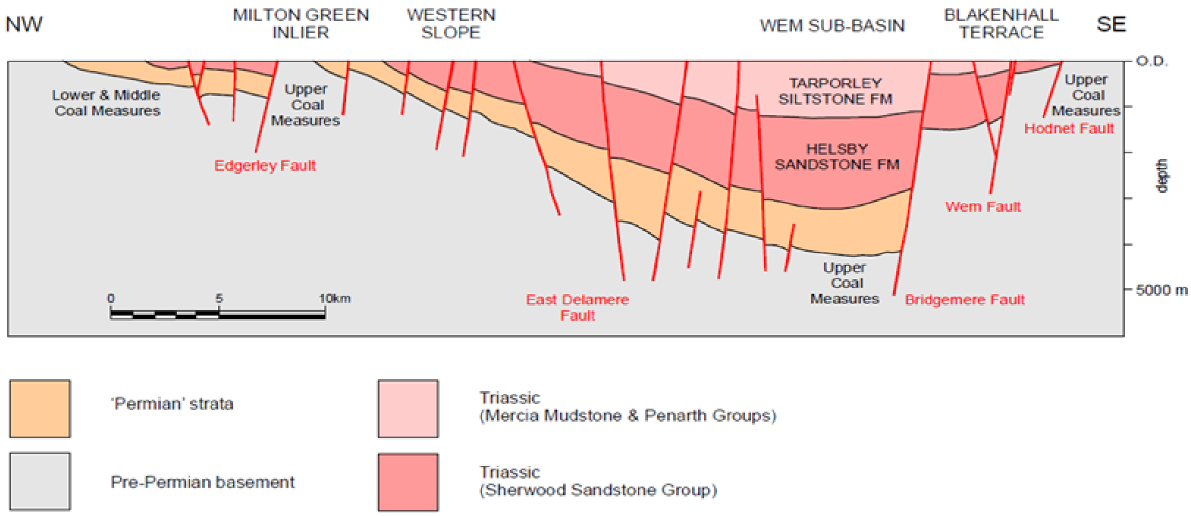

Figure 3: Geological Cross-Section through the Cheshire Basin (after Plant et al., 1999)

2.1 Wells, Temperature and Thermal Gradient

Borehole data for the basin are limited with only the Prees and Knutsford boreholes (Table 1) having proved the entire succession of the basin fill or penetrated the basin floor. Temperature data from four boreholes (Plant et al., 1999) over a range of depths in meters below ground level (mbgl) are shown in Table 1 and Figure 4. Borehole temperatures taken from these wells are uncorrected and therefore do not represent true formation temperature. During the drilling of a borehole, circulated drill fluid invades the surrounding formation causing temperatures to be suppressed. In addition, prior to any logging operations the well is circulated and flushed clean with water typically at a lower temperature than that of the surrounding formation (Bonte et al., 2012). Taking the raw temperature data for the Cheshire Basin is likely to be suppressed by several °C, and therefore provides a conservative estimate of temperature at depth. Figure 4 shows that temperatures of 40ºC will be reached within the Cheshire Basin where the aquifer is present at depths of around 1.5km. Figure 5 shows a line of best fit through the data. Forecasting this trend line allows estimates of the temperature likely to be encountered at greater depths. In the deepest parts of the Cheshire Basin where the base of the Permian sandstone lies at depths of around 4.5km, temperatures approaching 100ºC could be expected (Figure 5).

Table 1: Depth and Temperature data for boreholes in the Cheshire Basin (after Plant et al., 1999)

Prees SJ53SE3		**Burford SJ65SW13**		**Elworth SJ65SW53**		**Knutsford SJ77NW4**	
Temperature ˚C	Depth mbgl	Temperature ˚C	Depth mbgl	Temperature ˚C	Depth mbgl	Temperature ˚C	Depth mbgl
53	1731	26	668	36	1089	27	715
56	1932	28	751	39	1318	31	909
59	2164	30	837			39	1500
62	2396					43	1803
66	2750					45	2000
70	2889					51	2230

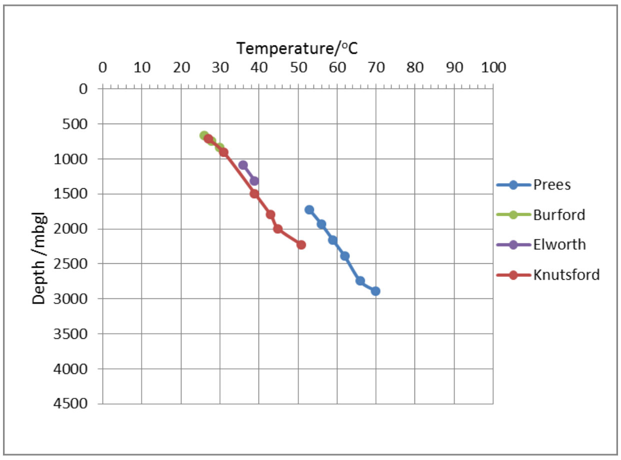

Figure 4: Depth temperature profiles in the Cheshire Basin

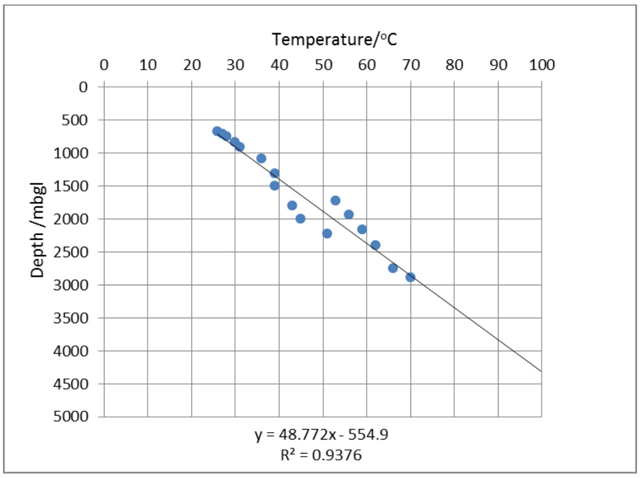

Figure 5: Depth temperature profiles in the Cheshire Basin. These temperatures are based on uncorrected temperature data.

2.2 Cheshire Basin Aquifers

Sandstones of Permo-Triassic age form the second most important aquifer in the UK, supplying approximately 25% of licensed groundwater abstractions in England and Wales (Monkhouse and Richards, 1982). These aquifers are present within the Cheshire

Basin at depths which means that they have potential as geothermal reservoirs. The Triassic Sherwood Sandstone Group comprises the Helsby, Wilmslow and Kinnerton sandstones and the Permian Collyhurst Sandstone. The Triassic and Permian sediments are at their thickest approaching 2km and 1km in thickness respectively in the south eastern part of the basin. This is the deepest part of the basin and here the Triassic and Permian sediments are overlain by around 1km of the Mercia Mudstone Group (Figure 3). In the northern and central parts of the basin the Triassic and Permian aquifers are separated by the Manchester Marl that is 148m thick at the Knutsford borehole [SJ77NW4] yet absent in the Prees borehole [SJ53SE3] (Colter and Barr, 1975). This formation may act to prevent flow between the aquifers above and below. In the south western part of the basin, the aquifer is referred to collectively as Permo-Trias because it is composed of Permian and Triassic sandstones that are undifferentiated and are in hydraulic continuity.

The Triassic Sherwood Sandstone Group is a major aquifer in North West England (Griffiths et al., 2003). In the extreme southwest of the basin, this formation is 1615m thick in the Knutsford borehole and 957m thick in the Prees Borehole (Evans et al., 1993). Borehole yields are variable with rare failures (i.e. dry boreholes). Yields of 50 l/s from the Triassic Sherwood Sandstone Group are commonplace for large diameter boreholes and some have yields in excess of 100l/s. Groundwater abstraction from the Sherwood Sandstone Group in the northern part of the basin peaked in 1960 at 93 mega litres per day (Ml/d) but has declined since to 20Ml/d in 1982 (Plant et al., 1999). Some ingress of saline water (and contamination of potable supplies by saline water) has occurred beneath the large conurbations of Merseyside due to historic over-abstraction. Over-abstraction was due to heavy water use by industrial processes and although industrial use of groundwater has declined due to a combination of changes in the nature of industrial operations, industrial decline and improved plant efficiency once an aquifer becomes contaminated (in this case by saline water) it is difficult to reverse this situation.

The underlying Permian Collyhurst sandstone is of continental aeolian origin, this formation is 557m thick in the Knutsford borehole [SJ77NW4] and 515m thick in the Prees Borehole [SJ53SE3] (Evans et al. 1993) in the extreme southwest of the basin. The Permian Collyhurst Sandstone has supported yields of 20 to 30l/s from large diameter boreholes (Plant et al., 1999).

The proposed model for groundwater flow in the Cheshire Basin is a regime dominated by density driven cells moving downwards from sources within the Mercia Mudstone Group with some thermal perturbations resulting from reduction in density and viscosity with increased temperature towards the base of the basin fill. The outlet for this circulation system is thought to be around the margins of the basin into the active freshwater circulation system (Plant et al., 1999) It should be noted that groundwater abstracted from depth for the purposes of geothermal exploitation is likely to be saline and therefore well infrastructure should be designed accordingly to accommodate potential problems associated with scaling and corrosion.

2.3 Analogue Data – East Irish Sea Basin (EISB)

The Cheshire Basin is contiguous with the offshore East Irish Sea Basin (EISB); linked by a narrow neck comprising the Wirral Peninsula and coastal areas of Merseyside (Figure 1). The EISB has been well explored for oil and gas and has 14 producing gas and oil fields that range in size from several tens of billion cubic feet to trillion cubic feet (Gluyas and Hichens, 2003). All of the EISB fields produce from the Triassic Sherwood Sandstone interval, although at least one discovery has been made and tested in the deeper Permian Collyhurst sandstone in the northern part of the basin. Few wells have penetrated into the Carboniferous and although gas shows have been recorded nothing has been classified as a discovery at this stratigraphic level. The source of most of the gas in the basin is without doubt the Carboniferous Westphalian coals while some of the gas and all of the oil (in the south of the EISB) come from the basal Namurian Holywell Shale (Armstrong et al, 1995).

The value of the EISB as an analogy for the Cheshire Basin comes from the numbers of wells drilled and the reservoir information collected. The extensively explored and exploited Triassic Sherwood Sandstone is for the most part high quality reservoir (Table 2). However in the north of the area some degradation of reservoir quality is apparent with pore-bridging and pore-filling illite cement in the sandstones of parts of North Morecambe and Millom. Cowan and Bradney (1997) have interpreted this cement as the product of local mineralising fluids. Apart from the area which suffered the localized cementation, measured flow rates in wells drilled elsewhere in the basin are substantial. The oilfield's peak production from Douglas was 95 ls^{-1} from 11 wells and for Lennox 76 ls^{-1} from 7 wells of light, low viscosity oil (DECC website, 2014). These flow rates are for oils with similar viscosity to water from wells of outside diameter only 9 $^{5}/_{8}$" (Yaliz and McKim, 2003).

Table 2: Reservoir properties for East Irish Sea oil and gas fields (compiled from data in Gluyas & Hichens, 2003)

Field	Reservoir Interval	Net to Gross	Average Porosity	Average Permeability	Data Source
		(fraction)	(%)	(mD)	
Douglas	Triassic Sherwood	0.95	18	2000	Yaliz & McKim, 2003
Hamilton	Triassic Sherwood	1	15	1300	Yaliz & Taylor, 2003
Hamilton North	Triassic Sherwood	1	15	320	Yaliz & Taylor, 2003
Lennox	Triassic Sherwood	0.95	15	about 1000	Yaliz & Chapman, 2003
North Morecambe	Triassic Sherwood	0.92	10	100	Cowan & Boycott-Brown, 2003
		0.92	11	0.5	illite affected interval
South Morecambe	Triassic Sherwood	0.79	14	150	Bastin et al, 2003
Millom	Triassic Sherwood	not recorded	9	0.5	Cowan & Bradney, 1997

2.4 Basin Centre Gas & Other Petroleum Possibilities

Between the Permo-Triassic aquifers and Lower Carboniferous levels within the Cheshire Basin lie Coal Measures strata (MacCarthy et al., 1996) and the Lower Namurian hot shales that together have sourced the oil and gas accumulations in the East Irish Sea, Staffordshire, Shropshire and the UK East Midlands. These organic rich strata are mature for petroleum generation. Conventional and unconventional (residually trapped gas, dissolved gas) natural gas resources are possible throughout the basin. If found to co-exist with a geothermal resource, the presence of natural gas could provide a useful high-calorie energy source and used directly for combined heat and power schemes, or alternatively could be fed into the local gas supply network. Recent estimates on the geothermal potential of the Cheshire Basin suggests that temperatures of up to 100°C are likely to be encountered at depths of around 4.5km, but concomitant production of methane could reduce the depth required for abstraction wells by offering an alternative for increasing the resource temperature.

In detail, the distribution of both Coal Measures and Namurian strata beneath the Permo-Triassic of the Cheshire Basin are uncertain. British Geological Survey information (Plant et al, 1999; BGS, 2002) indicate virtually the whole of the Permo-Triassic Basin to be underlain by Westphalian and older deposits while Abdoh et al (1990) and Mikkelsen & Floodpage (1997) suggest the deep south eastern part of the basin is bare of Upper Carboniferous with Permo-Triassic lying on Lower Palaeozoic low-grade metamorphic rocks. This latter analysis was based upon interpretation of gravity data and poor quality seismic data. The presence of extremely thick coal-bearing strata at surface immediately to the east of the Cheshire Basin across the Wem-Bridgmere-Red Rock Fault system into North Staffordshire also makes this interpretation unreliable. Only two wells have penetrated the base Carboniferous; Prees-1 (faulted base of Carboniferous, Westphalian D and Stephanian red beds at 3720m, Silurian strata beneath) and Milton Green (base of Carboniferous at 1500m, Ordovician rocks beneath). It is not clear which of these two very different interpretations is correct but what is clear is that the area has abundant oil and gas shows with a few wells having been successfully flow tested (Figure 6).

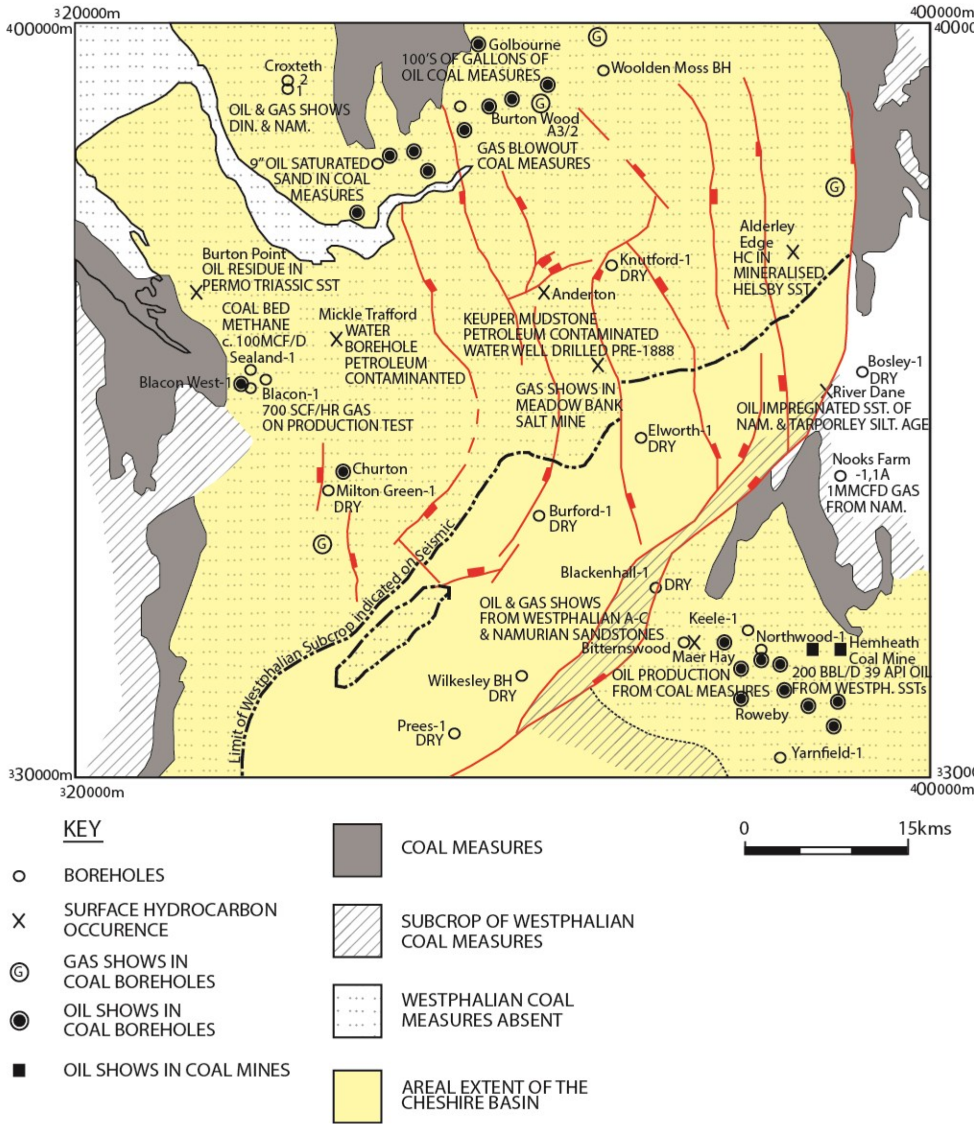

Figure 6: Distribution of gas and oil shows and tests in the Cheshire Basin (reproduced from Mikkelsen and Floodpage, 1997). The absence of Westphalian source rocks form an area stretching from Prees-1 in the south to Bosley-1 in the east is challenged by BGS authors.

3. RESOURCE POTENTIAL

Exploration for geothermal targets includes the detection and delineation of potential reservoir aquifers that have sufficient thickness, permeability and temperature for the proposed end use. An intrinsic transmissivity value (a product of the intrinsic permeability and the saturated thickness of the aquifer) of 5Dm has been suggested by Downing and Gray (1986) as the lowest practical limit for geothermal developments. Ideal site characteristics can be summarised as a reservoir with a minimum thickness of 200m and a transmissivity of 10 to 20Dm at depths of around 2 to 2.5km (Downing and Gray, 1986). Clearly there are sufficiently thick aquifers lying at suitable depths within the Cheshire Basin but there are limited transmissivity data. However the interpretation of geophysical logs from Cheshire Basin boreholes indicates transmissivity values of at least 10Dm (Allen et el., 1985).

The temperatures encountered at depth in the Cheshire Basin are unlikely to be sufficiently high for efficient power generation using currently available technology but could be used for the provision of heat, unless resources are discovered that include hydrocarbons. The geothermal resource (Ho) can be calculated using a volumetric approach (Gale et al., 1985) (Eqn.1)

$$Ho = [\phi \delta_f c_f + (1-\phi)\delta_m c_m] V(T_r - T_0)$$

Where ϕ = fractional porosity; δ_f = density of pore fluid Mg m^{-3}
c_f = specific heat of fluid J g^{-1} °C^{-1}; δ_m = density of matrix Mg m^{-3}
c_m = specific heat of matrix J g^{-1} °C^{-1}; T_r = temperature of reservoir °C
T_0 = temperature of ground surface °C; V = volume of reservoir m^3

Equation 1: Method for calculating thermal resource from a geothermal aquifer.

$$Io = Ho.F(T_r - T_j)/(T_r - T_0)$$

Equation 2: Method for calculating the exploitable resource from a geothermal aquifer

The exploitable resource (Io) is a function of the aquifer properties, abstraction method (F) and the reject temperature (T_j) of the spent geothermal fluid (Eqn.2).

Data from the Paris Basin suggest that F = 0.33 and 0.1 for a doublet and singlet wells respectively. The following figures have been calculated by the British Geological Survey and assume reservoir temperatures greater than 40°C, a reject temperature of 25°C for a doublet system comprising an abstraction and reinjection well. An initial assessment of the geothermal resource of the Cheshire Basin (Gale et al., 1985) suggested that the total and exploitable resources using the limited data available at the time were 45 x 10^{18}J and 6 x 10^{18}J respectively. Detailed seismic interpretation (Plant et al., 1999) linked with reassessment of existing data and new modelling techniques allowed for a new estimate of the geothermal potential (Rollin et al., 1995) which is more than double the previous estimate (Table 3) and shows a promising resource.

Table 3: Geothermal Resource within the aquifers of the Cheshire Basin (After Rollin et al., 1995)

Aquifer	Area km^2	Total Geothermal Resource (10^{18} J)	Exploitable Geothermal Resource (10^{18} J)	Millions of Barrels of Oil Equivalent MBoE*
SSG Triassic	677	36	8	1333
CS Permian	1266	39	9	1500
	Totals	**75**	**17**	**1833**

*Assumes 200M barrels of oil = 1.2 x 10^{18} J

4. DEVELOPMENT OPTIONS AND OBSTACLES

The effective use of deep geothermal heat requires an appropriate distribution network (such as a district-wide heat network). This works best in populated areas such as city centres where stand-alone micro-generation systems may be subject to space, emissions or noise constraints and where there is a greater density of energy demand. Barriers to the development of district heat networks include technical, economic, political and social factors. Economics in particular provide the greatest barrier to any initial geothermal project startup. The Deep Geothermal Review Study of the UK (Atkins, 2013) assessed UK deep geothermal exploration for power from an investors view, determining it to still be in the "research" phase (Figure 7). Low-enthalpy resources can be regarded in a similar manner and have been included on the same Figure.

Current planned low-enthalpy schemes will require significant funding for exploration activities designed to reduce the risk and uncertainty of developing the geothermal resource. A significant knowledge and experience gap exists between operational schemes (i.e. Southampton) and those still within the research phase, highlighting the relatively juvenile status of geothermal exploration within the UK. However, recent interest from several Local Authorities and Councils has begun to pave the way for future development of the UK's low-enthalpy geothermal resources. The approach these government authorities take considers technical and social barriers early on in the research phase.

5. CONCLUSIONS

The Cheshire Basin covers an area of approximately 3500km^2, and is infilled with a thick (~4.5km) sequence of Permo-Triassic sediments. Historically the basin has been of high economic importance, in part due to thick, laterally continuous transmissive sandstone units (such as the Collyhurst Sandstone and Sherwood Sandstone) forming large potable water sources supplying large conurbations located on the fringes of the basin. In addition, economic value has been found in the major halite resource that is contained within these strata. The temperature gradient across the basin suggests at depths of 4.5km, temperatures of 100°C can be reached. These temperatures alone form a tantalising glimpse at the low enthalpy geothermal resource potential of the basin.

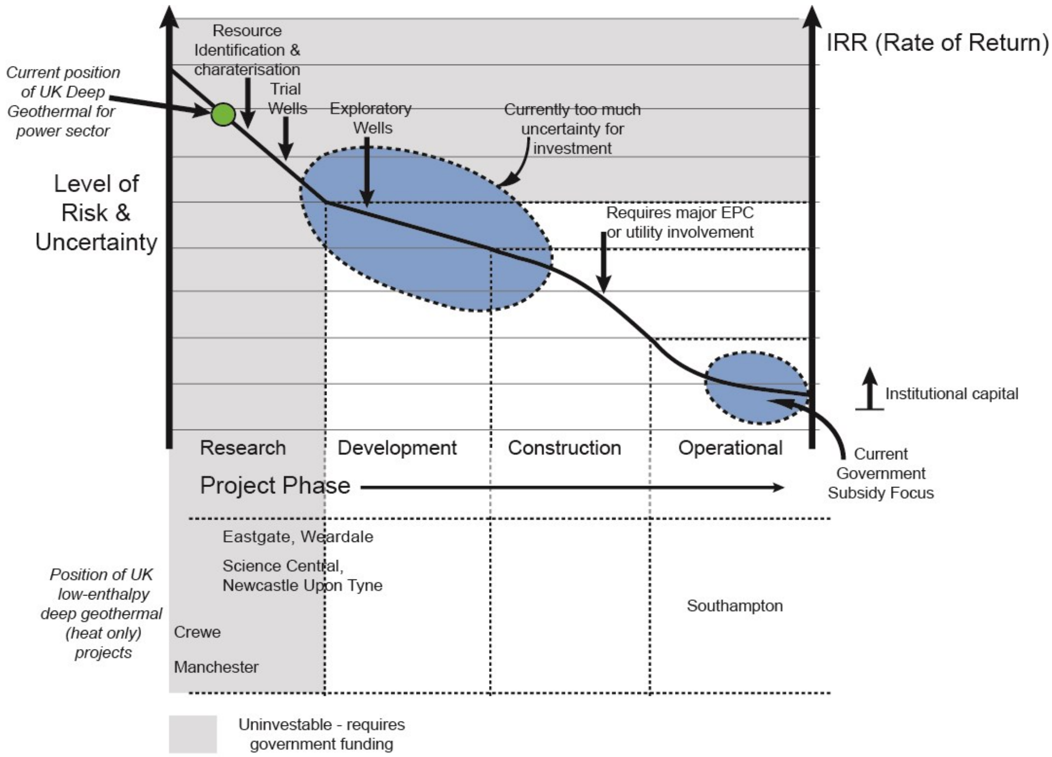

Figure 7: Investor view of geothermal resource exploitation (adapted from Atkins, 2013). Both geothermal for power and geothermal for heat only are considered.

The hydrocarbon prospectivity of the Cheshire Basin has previously been assessed due to the lithological and structural similarities with the neighbouring East Irish Sea Basin (EISB). The EISB contains 14 producing oil and gas fields, the source of which is the underlying Carboniferous strata. The Cheshire Basin is surrounded and underlain by Carboniferous rocks, including the Westphalian Coal Measures and Lower Namurian Holywell Shales. Therefore the potential for hydrocarbon reserves to be located under parts of the Cheshire Basin also exists. The potential presence of natural gas in association with warm geothermal waters in the Cheshire Basin could present an unconventional hydrocarbon resource; the gas could be co-produced and used in combination with the geothermal heat to flash water to steam for power generation, or could be sold into a gas supply network.

Transmissivity data is currently insufficient to determine if a geothermal scheme can be supported. However, the limited data that are available suggest flow rates of 10Dm are possible (double the required flow rate suggested by Downing and Gray, 1986). Notwithstanding the additional potential for hydrocarbon extraction and therefore additional energy supply, water temperatures within the Cheshire Basin at 4.5km are sufficient for heating purposes only. The total heat resource of two major productive sandstone units has been calculated to be 75 x 10^{18} J, with an exploitable resource of 17 x 10^{18} J. This heat could be utilised within a district heat network not dissimilar to that implemented in Southampton. The heat networks would require well populated centres where heat demand is high.

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