TARGETS FOR GEOTHERMAL ENERGY EXPLOITATION IN THE UK

This submission reviews aspects of geothermal resources that are relevant to the choice of values used in Professor MacKay's book *Sustainable Energy - Without the Hot Air*[1] (herein *SEWTHA*) and DECC's 2050 *Pathways Analysis*[2] (herein *Pathways*).

(i) Magnitude of the UK's geothermal resource

SEWTHA and *Pathways* are primarily concerned with the use of geothermal energy for power generation. Only hot dry rock resources are capable of efficient power generation although hybrid renewable power concepts and binary cycle power generators are making hot aquifers increasingly relevant. The use deep geothermal energy for direct heating is not considered explicitly in *SEWTHA* and *Pathways* allows for 1% contribution from this source.

Hot Dry Rock (HDR) resources

SEWTHA adopts the estimate of 25 TWh/y published by MacDonald et al.[3] (data from Newton[4]) while the 2050 Level 4 trajectory in the *Pathways* is more optimistic at 35 TWh/y. Several estimates of the UK geothermal (or HDR) resource have been published[3-7], and they vary widely depending on a range of factors (although the assumptions are not always clear). Here we discuss whether the maximum *Pathways* target of 35 TWh/y is sufficiently ambitious.

Perhaps the most detailed evaluation of the UK geothermal resource was presented by Gale & Rollin[5] in the 1986 overview of the UK's geothermal research programme. They calculated the energy stored in UK rocks between the 100°C isotherm and 7 km depth (Hot Dry Rock Accessible Resource Base), estimated as 9.9 x10^6 TWh. Assuming 40% of the heat is recoverable[8] and heat to electric power conversion efficiency is 10%[8] the UK resource is 45 TWh/y, exceeding the most ambitious *Pathways* target. A review of renewables in UK by the Institute of Electrical Engineers in 2002 concluded that the technical potential (i.e. "the upper limit that is unlikely ever to be exceeded") of geothermal resources is 210 TWh/y[9].

It is widely assumed in the literature that all the UK's large HDR resources have been identified, despite the sparseness of deep drilling. Cornwall is considered to have the best resources (77% of the heat between the 200°C isotherm and 7km) but there are compelling reasons to believe that other very good resources remain to be identified:

- The considerable promise of the granites in the East Grampian Highlands of Scotland as HDR prospects was diminished when boreholes in these granites indicated relatively low heat flows of ~70 mW/m^2 compared with ~120 mW/m^2 for Cornwall. Predictions from concentrations of radioelements in surface rocks indicated that some Grampian granites produce more heat than the Cornish granites (typically 6-7 μW/m^3 compared with 4-5 μW/m^3). Various explanations of this paradox were advanced during the studies of the 70s and 80s, but the depression of the geothermal gradient due to the persistent thermal effect of a thick ice sheet covering the Grampians[10] was largely overlooked, despite its use as an explanation for concave geothermal gradients in a deep borehole in Scotland as early as 1939[11]. This phenomenon probably affected much of northern Europe[12] and estimation of the resource requires drilling to ~2km depth in the Grampian Highlands to measure geothermal gradients below the glacially affected zone[13]. If deep heat flow in the Grampians turns out to be comparable to Cornwall then the UK's high enthalpy resource might be double that of current estimates.

- The world's largest HDR prospect within the Cooper Basin of South Australia[14] might not have been discovered without detailed heat flow information from hydrocarbon prospecting activities, and the region is now expected to support 12.5 GW of generating capacity[15]. Heat in the Cooper Basin comes from a granite body in basement rocks at 4-5km depth covered by an insulating blanket of basin infill sediments including many coal seams. The UK geothermal research programme preceded the discovery of geothermal potential in the Cooper Basin, and analogues of the special geological configuration were not explicitly sought. There are candidate basins in the UK that deserve investigation, but will require the acquisition of more heat flow and heat conduction information from informative depths.

In summary, despite extensive studies in the 70s & 80s, the UK's HDR geothermal resource is not robustly defined, and large resources, including some with high enthalpy potential, *may* have been missed. Furthermore, the available database leads to widely varying assessments of the available and potential HDR resource.

Aquifer geothermal resources

The potential for low enthalpy geothermal energy in the UK's known hot sedimentary aquifers (HSAs) has been reviewed and 130,000 TWh of resources above 20°C have been estimated[16]. Locally some of these HSAs may be exploited for direct heating purposes but the impact of these shallow aquifers is unlikely to be large on a national scale. The focus of this study was on relatively accessible aquifers with good natural rock characteristics, including porosity and transmissivity. This led to the identification of several "potential geothermal fields", principally in Permo-Triassic sandstones.

Since this report[16] in 1986 extensive exploitation of HSAs in the Rhine Graben of Germany has been based on a different model, accessing hotter waters at greater depths (2-5 km) and artificially creating reservoirs by the process of stimulation. Application of this model to deeper UK HSAs, including those in the Lower Palaeozoic of the UK at 3-5 km depth, could lead to the identification of much larger resources. (At St Andrews University we are investigating the geothermal potential of Devonian aquifers in the Midland Valley graben of Scotland.)

The importance of *hybrid power plant* concepts has recently been recognised[17]. By combining another renewable energy source in a geothermal power plant, the potential of geothermal energy can be extended into aquifers that alone have too little heat resource for efficient power generation. Aquifers with temperatures below 120°C can thus be made viable. An example is the geothermal-biogas power plant at Neuried (Germany)[17].

Sedimentary aquifers may also have significant roles in the large-scale *seasonal storage* of heat, particularly where they are located near large power stations.

As with high enthalpy resources, we may not yet know where all the best low-intermediate enthalpy resources are located. New models for deep aquifers exploitable using enhanced reservoir stimulation techniques might lead to significant additional resources, some of which may have potential for heat and power generation.

Minewater resources

Disused collieries are environmental hazards and are often treated to remove pollutants, but useful heat is typically discarded. PB Power estimated the *sustainable* resource in Scotland to be up to 1708 GWh per year[18], amounting to ~3% of the Scotland's heat load. Most of this resource lies close to urban areas and demand in the Central Belt. The total UK minewater resource could make a significant contribution if replicated in other deep coalfields in the north of England, Midlands and South Wales.

Much progress has been made in the efficient exploitation of geothermal energy since the peak of the UK geothermal research programme nearly 25 years ago, and it now seems likely that the UK resources for both high and low enthalpy geothermal may have been significantly underestimated. A programme of research is warranted that builds on the available data in applying new models to the location of resources. Furthermore, variability in the literature on estimated resources indicates considerable uncertainty and there is need for an agreed basis for quantitatively evaluating the potential for geothermal energy in the UK. In the meantime, the highest target in *Pathways* for geothermal electricity generation should be considered conservative and possibly a significant underestimate.

(ii) Sustainability of geothermal resources

Whether geothermal resources are considered *sustainable* or *mineable* depends on the rate of recovery following exploitation, and *SEWTHA* takes this to occur over geological spans of time. Relevant here are the conclusions of a recent review paper[19] by Professor Ladislaus Rybach of ETH, Zurich, probably the leading authority on the recovery of geothermal systems:

> "In summary, the following general comments about geothermal regeneration can be made. Production of geothermal fluid and/or heat from a reservoir/resource decreases its fluid/heat content, but also increases the natural recharge rate into created pressure and temperature sinks (i.e. dynamic recovery). A new and sustainable equilibrium condition can be established. The recovery process begins after production stops, driven by natural forces resulting from pressure and temperature gradients. The recovery typically shows asymptotic behaviour, being strong at the beginning and slowing down subsequently, with the original state being re-established theoretically only after an infinite time. *However, practical replenishment (e.g. 95% recovery) will be reached much earlier, generally on time-scales of the same order as the lifetime of the geothermal production systems*."

These findings relate to both HDR and lower enthalpy systems, and indicate that geothermal production can be made effectively sustainable in the long term if exploited over a cycle that provides adequate recovery time.

(iii) Implications for *Pathways* targets and the DECC Calculator

Scenario 4 for geothermal energy electricity generation in *Pathways* and the DECC 2050 Calculator reaches 35 TWh in 2030 after which it remains flat, consequently the geothermal contribution is destined to remain small. The survey of published estimates above suggests that the figure may be conservative and not sufficiently ambitious for the exercise, and that it should more properly fall between 45 and 210 TWh/y.

An independent approach to assessing the 35 TWh/y limit is to consult analogous targets for comparative countries. The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) developed a scenario-planning model in 2008[20] (available in English). The model was updated in 2009[21] and the BMU's geothermal targets were set at 52.1 TWh in 2030 and 134.7 in 2050, with power generation representing 13% of the 2030 target rising to 28% by 2050.

The UK and Germany are broadly similar; the latter has nearly 150% of the UK's land area supporting a population about one third greater. Both countries have traditions of excellence in engineering, though the UK probably has more experience of extracting fluid resources from the top few kilometres of the Earth's crust through its large oil & gas industry. More importantly Germany does not posses an obviously rich geothermal resource. There is no current volcanic activity and much of the identified resource is low to intermediate enthalpy, mainly located in aquifers within the Rhine graben (so-called hydrothermal resources). The BMU model gradually shifts dependence from hydrothermal (mainly aquifer) sources to an increasing reliance after 2030 on high enthalpy deeper hot dry rock (HDR) resources. As it happens the UK has rather better HDR opportunities, with Cornwall hosting some of the best prospects in Europe. It is worth noting that Germany's geothermal industry is developing at a spectacular rate, particularly since a federal law in 2000 created a sound financial basis for geothermal development. Subsequent improvements to incentives, including generous feed-in tariffs, have accelerated this development[22].

The German geothermal power-generating target of 135 TWh/y falls near the middle of the UK HDR range of 45-210 TWh/y discussed above. In the spirit of ambitious agendas inherent in the *SEWTHA* and *Pathways* process, it is suggested that the more aspirational (but defendable) target of 135 TWh/y be adopted in place of the current 35 TWh/y for Trajectory 4 in 2050. A more “heroic” target might be 210 TWh/y.

The geothermal contribution of 1% to some of the heating and cooling pathways in *Pathways* has not been evaluated.

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