Heat mining or replenishable geothermal energy? A project for advanced-level physics students

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ABSTRACT There is growing interest in the use of low enthalpy geothermal (LEG) energy schemes, whereby heated water is extracted from sandstone aquifers for civic heating projects. While prevalent in countries with volcanic activity, a recently proposed scheme for Manchester offered the perfect opportunity to engage students in the viability of this form of energy capture. This article details how second-year advanced-level physics students (A2, age 17–18) were given the freedom to design their own experiments and analyses of the proposed LEG scheme. The project provided opportunities for the students to improve their understanding of thermal physics and the 'How science works' sections of the A2 syllabus, while building their teamworking skills.

While watching the local television news two summers ago, I saw a short feature about a proposal to use geothermal energy to heat 6000 homes in Manchester. Like most teachers, I tell my students that this type of energy is predictably popular in countries with high levels of volcanic activity, for example Iceland. To hear about the possibility of its use in the slightly less volcanic North West of England was intriguing, so I began thinking about ways in which my physics students at Cronton Sixth Form College in Cheshire could investigate the viability of the Manchester scheme.

About low enthalpy geothermal energy

The type of geothermal energy proposed for Manchester is known as low enthalpy geothermal (LEG). This uses much lower temperatures and pressures than the traditional geothermal energy plants that we study in GCSE Physics (BBC News, 2012). In LEG systems, water (or saline solution) at temperatures less than 100 °C is drawn from depths of several kilometres where it resides as aquifers within regions of porous sandstone. This water is used to provide district heating, replacing individual hot water boilers in homes, offices, hospital and schools. An LEG scheme has twin boreholes: one extracts the hot saline solution, while the other re-injects the cooled saline back underground to maintain high enough fluid pressures for extraction. Examples of this type of geothermal heating scheme can be found in Southampton and Paris (Boyle, 2004). The Southampton scheme, in operation since 1981, draws salt water at 76 °C from around 2 km below the city, providing 2 MW of thermal power. The salt water passes through a heat exchanger where it transfers heat energy to water in the district-heating scheme. The scheme heats buildings within a 2 km radius of the salt water well, including the civic centre and swimming pool. The LEG system in Paris is much more extensive, consisting of more than 50 group-heating schemes, each designed to supply 3–5 MW for a period of 30–50 years.

Experimental activity

The students were surprised to hear about this plan and keen to investigate. I decided to use this as an opportunity for group work, so divided the class into teams of four. Each team was tasked with playing the role of an engineering consultancy company that had been employed by the local council to investigate the efficiency and longevity of the system. I made it clear that all members of the team must complete some experimental work in addition to organising themselves by nominating a leader and assigning responsibilities for collecting and collating data and presenting the work as either a report or technical poster.

Their first task was to acquire samples of sandstone of the type found 2 km below Manchester. Geological diagrams indicated that this sandstone layer emerges very close to the college, at Pex Hill Quarry Nature Reserve. The proximity of the quarry allowed the students to collect sandstone samples. However, additional free sandstone samples were also sourced from quarrying companies via their websites.

Next, the students had to design experiments to investigate how much heat energy could be stored within the sandstone. This required them to use their knowledge of specific heat capacity from their A-level Physics course. When planning their investigations, most groups realised that they would also have to find the density of sandstone in order to estimate the mass of the stone from which the heat would be extracted.

Measuring the specific heat capacity of sandstone

The students elected to approach this task by calculating the specific heat capacities of both wet and dry sandstone. For dry sandstone, the samples were heated in an oven at 80 °C. For wet sandstone, the samples were heated in a water bath at 80 °C. In both cases, the temperature of the stones was measured with a digital infrared thermometer. Each hot stone was then dropped in a beaker of water at room temperature T_r, and the temperature of the water monitored with a thermometer (Figure 1).

The specific heat capacity of the sandstone was estimated by measuring the heat energy transferred when a hot stone of known mass m_s was placed in water of known mass m_w and known initial temperature T_r. The temperature of the stone will fall by ΔT_s and the temperature of the water will rise by ΔT_w until equilibrium is achieved. This point is identified by observing the maximum (or equilibrium) temperature T_e of the water. So, for example, ΔT_s may be $(80\,°\mathrm{C} - T_e)$. Since the specific heat capacity of water, c_w, is well known, the specific heat capacity of the sandstone, c_s, can be found from:

heat energy lost by the sandstone = heat energy gained by the water

$$m_s c_s \Delta T_s = m_w c_w \Delta T_w$$

provided it can be assumed that no heat is lost to the surroundings.

The students investigated the best size of stone and volumes of water when designing their experiments. Examples of the students' experimental set-up are shown in Figure 2.

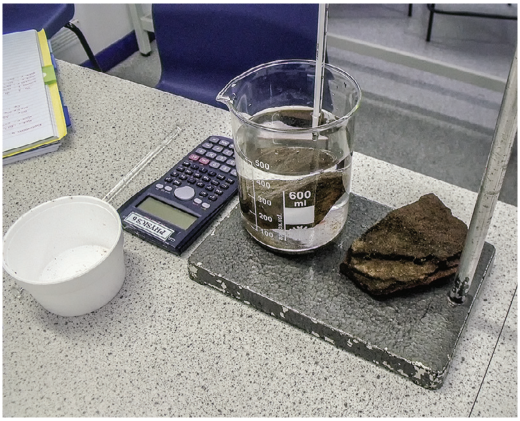

Figure 2 Measuring the change in temperature, ΔT_w

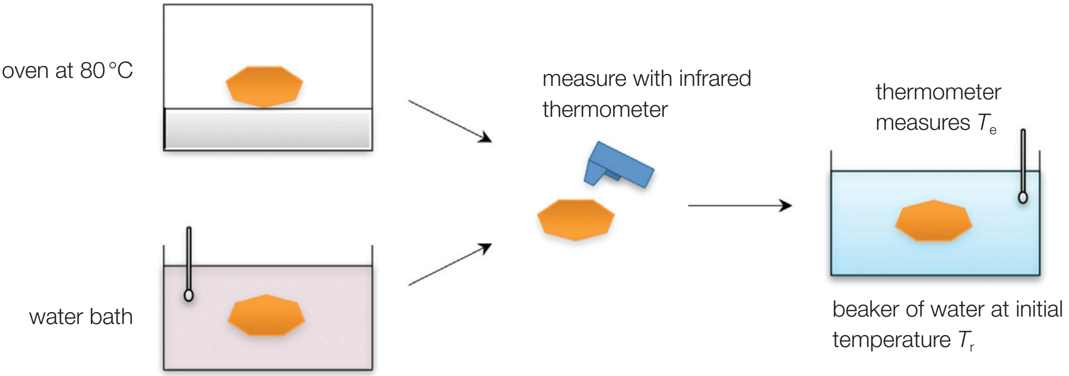

Figure 1 Measuring heat transfer

Measuring the density of sandstone

The mass of the sandstone samples was measured with a mass balance and the volumes were estimated using the displacement technique. The density was found using the standard relationship:

density = mass/volume

Experimental results

As shown in Table 1, the students' experimental results tended to overestimate the literature value, which is to be expected for poorly insulated beakers, and may also be influenced by factors including the porosity of the stone.

Table 1 Heat capacity results

Specific heat capacity	Students' value	Literature value
Dry sandstone	$1200\,\mathrm{J\,kg^{-1}\,K^{-1}}$	$920\,\mathrm{J\,kg^{-1}\,K^{-1}}$
Wet sandstone	$1640\,\mathrm{J\,kg^{-1}\,K^{-1}}$	N/A

The students' calculated densities for dry sandstone were generally quite consistent at about $2100\,\mathrm{kg\,m^{-3}}$.

Analysis of the LEG scheme

The student groups then investigated the viability of the Manchester LEG scheme using a variety of approaches, one of which is detailed here.

In this calculation the students used their measured specific heat capacity of wet sandstone to calculate the thermal resource for a block of wet sandstone of volume $2\,\mathrm{km} \times 2\,\mathrm{km} \times 20\,\mathrm{m}$ at an average temperature of 80 °C, with a re-injection temperature of 10 °C. This is a good approximation of the real-world scenario proposed for Manchester. The students' analysis proceeded as follows:

- Calculate the volume of wet sandstone, $4 \times 10^6 \times 20 = 80 \times 10^6\,\mathrm{m^3}$.
- Mass of sandstone = density × volume $= 2323 \times 80 \times 10^6 = 2 \times 10^{11}\,\mathrm{kg}$.
- Calculate the heat energy extracted, $Q = mc\Delta T = (2 \times 10^{11})(1600)(80-10)$ $= 2 \times 10^{16}\,\mathrm{J}$.

Now, focusing on energy usage in heating a house:

- 24 kWh per day per person, so 48 kWh per household of two people (MacKay, 2009: 50–51).
- So assume that the power required at any given time is 2 kW.
- For 6000 houses, this is $12\,000\,\mathrm{kW} = 12 \times 10^6\,\mathrm{W}$.
- Power = energy/time.
- Time = energy/power $= 2 \times 10^{16}/12\,000 \times 10^3 = 1.7 \times 10^9\,\mathrm{s} = 54$ years.

In other words, the scheme would provide power for 54 years.

A renewable energy source or just heat mining?

Some students also considered the replenishment of the thermal stored heat in the sandstone aquifer due to the flow of heat from the centre of the Earth. A typical value for this is $50\,\mathrm{mW\,m^{-2}}$ (Boyle, 2004), which for an area of $4 \times 10^6\,\mathrm{m^2}$ gives a rate of heat transfer of 200 kW. This is not enough to replenish use at 12 000 kW. Based on the students' calculations, the thermal energy of the aquifer would be used 60 times faster than it is being replaced, indicating that the LEG scheme is actually heat mining rather than a replenishable energy.

Conclusion

This exercise was completed in one week at the end of the thermal physics section of the A2 Physics syllabus. There was genuine enthusiasm and interest in the project, with over half of the students requesting extra time in the laboratory during lunch and study periods. They worked well to design their experiments and I took the role of an adviser, only intervening if health and safety was an issue. This hands-off approach did result in some experiments needing to be modified or repeated. For example, when some students measuring the specific heat capacity of sandstone immersed the stone in too large a volume of water such that ΔT_w was too small to be measured.

Having overcome any experimental difficulties, the most challenging aspects for each group became agreeing the best method to analyse the viability of the LEG scheme and how to combine their individual laboratory reports into a coherent group report. When marking their group reports, I was able to assess both their knowledge of thermal physics and their ability to apply this knowledge to new problems. In previous class work, the students had used a calorimeter to calculate the specific heat capacity of aluminium and we had discussed energy transfers in fluids and solids. In the current geothermal experiment, they were able to combine this prior knowledge of specific heat capacity and energy transfer in a novel situation. This was an opportunity to improve their synoptic approach to problem solving, which is a key requirement for higher-level college physics courses. Indeed, their results and conclusions here demonstrated this increased understanding, both as a consequence of completing the task and of peer learning. In addition, the students developed many of the 'How science works' skills that contribute around 30% to their A-level mark, including: carrying out experimental investigations in a range of contexts, evaluating methodology and data, communicating information and ideas in an appropriate way, and appreciating the way in which society uses physics knowledge to inform decision-making. The last point, in particular, is difficult to cover in traditional lessons but aligned very well with this project, where the students made informed judgements as to the overall societal benefit, or otherwise, of the geothermal scheme.

At the end of the week I asked students to write a paragraph describing how they felt the project had gone. Two typical responses are given below.

This project has enabled me to experience what it was like to be given 'free rein' and has helped with my teamworking skills. I feel that, as a team, we were on top of our work and were all willing to put the effort in. I think the freedom came with a responsibility, and we stepped up to what we needed to achieve.

I have found this group project very valuable in experiencing a real-life application of physics. It allowed us to apply the theoretical science that we had learnt in class to provide an answer to a real question.

Perhaps surprisingly, most students were unconvinced that 54 years was a sufficient duration for the scheme and doubted its economic viability. They did, however, become more positive about its value following discussion of the rapid changes in UK fuel supply in just the past 100 years and potential future shortages of non-replenishables.

The use of local case studies for teaching about energy is a strategy previously used in my college, for example in an investigation into the effectiveness of a tidal barrage across the River Mersey (Dugdale, 2012). Similarly, this LEG viability project was an opportunity for students to apply their knowledge of thermal physics to a real-world problem. By empowering students to design their own experimental and analytical procedures within a broad framework of investigation, the project showed them that they possess the experimental and analytical skills to investigate the viability of the Manchester scheme from first principles. Furthermore, the project developed students' teamworking skills, especially when sharing results and presenting data. These are important aspects of the 'How science works' assessment outcomes and the Ofsted recommendations of employability.

In summary, the students' dedication to both the practical and analytical aspects of this investigation, coupled with their enthusiasm and freedom to find their own way to the solution, means this will be a returning activity at Cronton Sixth Form College.

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