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Technical Note: The Value of Heat and Geothermal Waters

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Abstract

Evaluation of proposed geothermal projects often requires a value to be assigned to waterborne geothermal heat or geothermal fluids. A methodology for valuing low enthalpy warm fluids (<90°C) is presented: the method uses a reference price for sale of waterborne district heating at a relatively high temperature (in this paper, we have assumed 70°C), and then discounts this price by the value of electricity that must be expended in a heat pump compressor to transfer heat from the source fluid to the target reference level. An alternative methodology is also presented, based on the exergy content of the geothermal fluid: this is arguably more theoretically justifiable but does not account for the real costs of running a heat pump. Compared with other sources of low carbon environmental heat, prospecting for deeper warm geothermal fluids will be favoured when drilling costs are low and electricity prices are high; shallow cooler fluids, coupled with the use of heat pumps, are economically favourable when electricity is cheap and drilling costs are high.

Keywords: Geothermal, heat, electricity, economics, heat pump, exergy

Introduction

Not all energy is equal and not all hot geothermal fluids are equal. A geothermal fluid at >180°C can be used to generate electricity via steam turbines: this electricity can be used to do work, to create light, to weld steel, to cook roast chickens and to power locomotives. It has a high exergy content and a high utility (and thus economic) value.

A fluid at 110°C can also be used to generate electricity via a binary power plant. This is somewhat more complex to achieve and the fluid thus has a lower value. A fluid at 80°C cannot (at present) be used efficiently to generate electricity, but it can be used to heat a conventional district heating network (DHN) or space heating system. A fluid at 40-60°C can be used for low-temperature space heating or for a 4th Generation DHN (see Glossary; Lund et al., 2014). A fluid at 25-30°C is much more restricted in its utility, but could still be used for some forms of aquaculture, swimming pool warming, de-icing or supporting a very-low temperature 5th Generation DHN (Boesten et al., 2019; Lindal, 1973).

All these fluids have a value, but their value reduces with decreasing temperature – this observation is intimately connected to the concept of exergy (Bodvarsson and Eggers, 1972; Falcone et al., 2013; Lee, 2001; Rant, 1956; Shukaya and Hammache, 2002): the amount of useful work that can be performed by a system.

We often need to assign a value to a geothermal fluid, to be able to evaluate whether a proposed geothermal project has an advantageous cost/benefit ratio. Conventionally, geothermal projects are evaluated by simply summing capital expenditure and operational expenditure over a project lifetime and dividing it by the quantity of heat produced to arrive at a Levelized Cost of Heating (LCOH). Examples of such calculated LCOH are 0.033 to 0.039 EUR per kWh_{th} for geothermal projects (excluding heat distribution networks) in Bavaria, Germany (Molar-Cruz et al., 2022) and 0.013 to 0.35 USD per kWh_{th} for deep geothermal direct use projects in the USA (Beckers et al., 2021). Arguably one of the most comprehensive analyses of the potential demand for and supply of geothermal district heating (GDH) is the USA GeoVision project (USDoE 2019, McCabe et al., 2019), which modelled LCOH of <0.125 to 0.175 USD per kWh_{th} for technically feasible GDH in the northern USA, but homed in on a lower market-feasible figure of 0.056 to 0.079 USD per kWh_{th} (interquartile range) for hydrothermal GDH. They argued that this latter estimate corresponded well with actual LCOH for American and European hydrothermal GDH schemes.

The methodologies described in this technical note aim at directly assigning a more intrinsic *value* to a given volume of warm water at a given temperature, rather than simply levelizing a whole project *cost*. These methodologies are not designed to replace the LCOH-type approach, but do yield a simpler, more direct value, which allows intercomparison of any technology based on waterborne heat, whether this is deep geothermal, shallow geothermal or the use of wastewater, seawater or river water with heat pumps.

We can take two approaches to the problem of assigning a value to the heat content of a geothermal water (or any water-based fluid) at a certain temperature. We will here only consider the use of heat for thermal purposes (heating), although Approach 2 could be extended to cover high-temperature fluids suitable for electricity generation.

Given the huge volatility of electricity and gas prices at the time of writing, we have elected in this paper to discuss electricity, district heating and gas prices dating from a more stable period, in the mid-late 2010s (Figure 1). We will, however, consider the impact of recent electricity price increases on the value of geothermal fluids. Note that, in the UK, electricity prices have typically been at least three times higher than mains natural gas prices: this, in part, reflects the typical thermodynamic inefficiency (EEA, 2015) in generating electricity from fossil fuels (coal having progressively given way to gas). It also explains why heat pumps have been relatively slow to gain traction in the UK: they need to deliver average coefficients of performance of >3 to generate significant cost savings for users (at least, in the absence of subsidy).

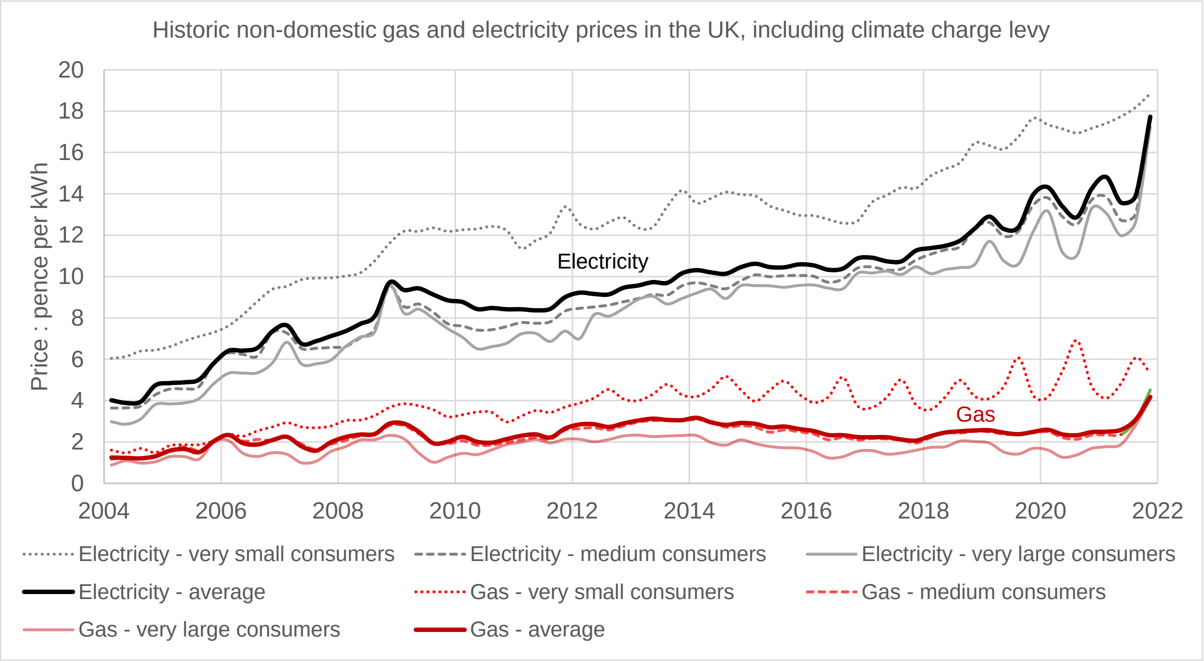

Figure 1. Prices of electricity and gas in the non-domestic sector in the UK, including climate charge levy, after data presented by (BEIS, 2022). Prices in pence per kWh (kilowatt-hour); 1 penny = 0.01 GBP.

Approach 1: Practical Approach - District Heat Pricing Discounted by Heat Pump Cost

Conventional (1st – 3rd Generation) district heat networks supply heat, via the distribution of a warm fluid, at a given relatively high temperature. Let us assume that provision of waterborne district heating is at a temperature $\boldsymbol{T_{ref}}$ and the price for that heating is $\boldsymbol{V_{ref}}$ (p per kWh_{th}). We can further assume that (given an ideally efficient heat exchanger) a geothermal fluid of temperature $\boldsymbol{T_{ref}}$ could be used to support such a district heat network. As recent examples of prices of district heating:

- In 2014, Eastcroft District Heating (a scheme based on waste incineration) in Nottingham was charging consumers 5.67 p per kWh_{th} plus a daily flat rate of 28.1 p. Assuming an annual consumption of 12000 kWh_{th} (OFGEM, 2020), this works out at an overall price of 6.52 p per kWh_{th} (Scholes, 2014). Assuming a lower consumption would, of course, increase the effective price.

- Swedish District Heating systems were charging 0.802 SEK per kWh_{th} in 2013 (7.7 p per kWh_{th}) (Li et al., 2015). These use a variety of heat sources – waste incineration, industrial waste heat and heat pumps in summer, and increasing components of fossil fuel in winter.

- In 2018, the average price being paid per UK consumer per year for district heating was £580, with heat being predominantly derived from natural gas or gas combined heat and power (CHP), with a lesser component of biomass (de Rochefort, 2018). SWITCH2 also cite this average annual cost of £588 per customer, but translate this into a price of 9.56 p per kWh_{th} (based on the consumption of only 6150 kWh_{th} per annum for a two bedroom flat - Allan, 2016). A study by Which (2015) found costs of UK district heating varied from 5.51-14.94 p per kWh_{th}, with an average of 11.04 p per kWh_{th}, based on a similar consumption.

- The US GeoVision project (McCabe et al., 2019, USDoE, 2019) constructed supply- and demand-side pricing curves for geothermal district heat in the US. The supply side curve was typically 7.5¢ to over 10¢ per kWh_{th}, but the equilibrium price was estimated at around 7.5¢ per kWh_{th}.

The above can be interpreted as “market” values. However, in many countries, such as the UK, district heating may be preferentially installed in social or state-owned housing projects, meaning that the price may be subsidised. A market value of $\mathbf{V_{ref}}$ is thus elusive: in this paper we have arbitrarily assumed that at a reference point in the mid-to-late 2010s:

$\boldsymbol{T_{ref}}$ = 70°C and $\mathbf{V_{ref}}$ = 9 p per kWh_{th} = 0.09 GBP per kWh_{th}

We have further assumed that the cost of electricity $\boldsymbol{E}$ = 11 p per kWh_e (Figure 1). Given the current (2022) extreme volatility of gas and electricity prices, in large part due to the ongoing

Russia-Ukraine conflict, it is the methodology, rather than the exact prices and values assumed, that is important for the purposes of this Technical Note.

Thus, we can say that waterborne heat at 70°C has a value of 9 p per kWh$_{th}$. A geothermal fluid at any lower temperature (say, 40°C) could be utilised, with the assistance of a heat pump, to supply heat to the district heating network at 70°C. The value of the geothermal fluid would be lower, however, by an amount equating to the cost of running the heat pump to elevate the temperature of the heat from 40°C to 70°C. The operational cost of running the heat pump to supply 1 kWh$_{th}$ of heat at 70°C can be simplistically taken as the cost the electricity required to run the compressor = $\boldsymbol{E/COP_T}$, where $\boldsymbol{COP_T}$ is the coefficient of performance of the heat pump at a temperature $\boldsymbol{T}$.

Thus, the value ($\boldsymbol{V_T}$) of waterborne heat at temperature $\boldsymbol{T}$ is given by discounting the value at 70°C ($\boldsymbol{V_{ref}}$) by the cost of the electricity input. The divisor of (1-1/$\boldsymbol{COP_T}$) renormalises $\boldsymbol{V_T}$ to 1 kWh$_{th}$ after the electrical energy (which also ends up as heat) has been subtracted.

$$V_T = \frac{(V_{ref} - E/COP_T)}{(1 - 1/COP_T)} \qquad [1]$$

Thus, at $\boldsymbol{T}$ = 40°C, if $\boldsymbol{V_{ref}}$ = 9 p per kWh$_{th}$, $\boldsymbol{E}$ = 11 p per kWh$_e$ and $\boldsymbol{COP_{40}}$ is 4, the value of the original heat at 40°C will be 8.33 p per kWh$_{th}$. In this case, 0.75 kWh$_{th}$ of waterborne heat at 40°C has been raised to 1 kWh$_{th}$ of heat at 70°C, by 0.25 kWh$_e$ of electrical energy powering the heat pump:

0.75 kWh of geothermal heat at 8.33 p + 0.25 kWh of electricity at 11 p = 1 kWh at 9.0 p

i.e. 6.25 p + 2.75 p = 9.0 p

In Approach 1, the heat pump is regarded as the "universal tool" by which heat can be transferred (at a cost) from one temperature to another. If we make another simplistic assumption: that the $\boldsymbol{COP_T}$ of a real heat pump is lower than the ideal Carnot efficiency by a factor $\boldsymbol{\varepsilon}$, we can calculate the value of 1 kWh$_{th}$ of waterborne heat at any temperature $\boldsymbol{T}$ (the asterisk $\boldsymbol{T^*}$ denotes that the calculation assumes temperatures are in degrees Kelvin (K)).

$$COP_T = \varepsilon \times \frac{T_H^*}{(T_H^* - T_C^*)} = \varepsilon \times \frac{T_{ref}^*}{(T_{ref}^* - T^*)} \qquad [2]$$

$\boldsymbol{\varepsilon}$ has been set to a value of 0.45 in this paper (see Abbreviations).We can see that (Figure 2), as the price of electricity increases, the value of the heat drops. The waterborne heat still has a positive value at temperatures below 0°C when electricity is 17 p per kWh$_e$, but not at 20 p per kWh$_e$. When electricity reaches 25 p per kWh$_e$ (as it has done in the UK at the time of writing), the waterborne heat loses its value at c. +15°C.

This is slightly simplistic, as we could argue that there are operational and maintenance costs to running a heat pump system, plus the spread cost of the initial capital investment. These could also be included in the value discounting factor but, in this paper, we will simplify the calculation by incorporating only the heat pump electrical cost. Other than the costs of the heat pump (our "universal tool" for changing the temperature of heat), no other costs (well drilling, submersible pumping) have been considered, as these are technology-specific and Approach 1 aims to compare the value of warm water-based fluids of different temperatures, irrespective of their origin.

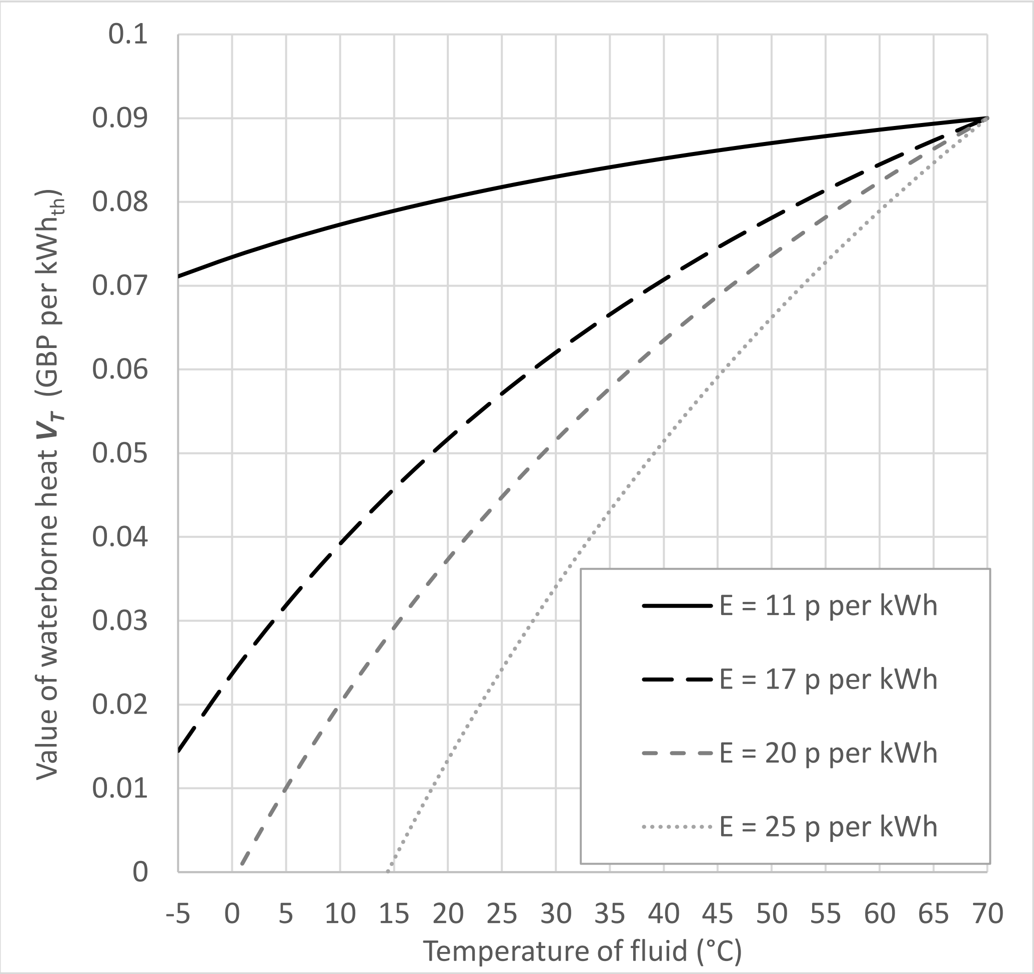

Figure 2. The value of 1 kWh_{th} of waterborne heat at various temperatures between -5 and +70°C, assuming that the value of heat at 70°C is 9 p per kWh_{th} and that $\boldsymbol{\varepsilon}$ = 0.45, for varying electricity prices. Note that the shapes of the curves are dependent on the ratio between $\boldsymbol{E}$ and $\boldsymbol{V_{ref}}$ (Equation 1) and not on their absolute values - one could generate similarly shaped corresponding curves for lower values of $\boldsymbol{V_{ref}}$.

How do we translate these values per $\mathrm{kWh_{th}}$ of waterborne heat to values per tonne or m^3 of warm water? Firstly, let us assume that there is an arbitrary temperature ($\boldsymbol{T_0}$) at which the value of waterborne heat is zero. In strict thermodynamic theory, this is absolute zero. In a closed loop ground source heat pump system, useful heat can be extracted (via anti-freeze solutions) at temperatures below 0°C. In conventional "wet" geothermal systems, one might choose to say that the cut-off for useful district heating applications is around 10°C, which still allows for useful heat extraction without incurring a risk of freezing in a heat exchanger.

One might now be tempted to say that the value of 1 tonne of warm water at 70°C is simply the number of $\mathrm{kWh_{th}}$ of heat released by dropping the temperature from 70°C to 10°C multiplied by $\boldsymbol{V_{70}}$. However, when we drop the temperature of the water from, say 70°C to 69°C we release approximately $\boldsymbol{c}$ = 1.161 $\mathrm{kWh_{th}}$ of heat (the specific heat capacity of water), with a value of 9 p per $\mathrm{kWh_{th}}$ = 10.45 p. But now the water is at 69°C and we need to use a heat pump (with an electricity input) to release the next 1.161 $\mathrm{kWh_{th}}$ at 70°C – this has a discounted value of 10.43 p. The water is now at 68°C. We thus break the calculation down into 1°C increments, all the way to the final step from $\boldsymbol{T_0}$+1°C to $\boldsymbol{T_0}$. deliver the remaining heat at 70°C.

Value of 1 tonne water at 70°C = $\sum_{i=T_0+1}^{70} V_i \times 1K \times c$ [3]

where $\boldsymbol{c}$ is the specific heat capacity of water in $\mathrm{kWh_{th}}$/tonne/K. By summing the value of all these increments, it turns out that 1 tonne of water at 70°C has a total value of 5.91 GBP, assuming $\boldsymbol{T_0}$ = 10°C, $\boldsymbol{V_{ref}}$ = 9 p per $\mathrm{kWh_{th}}$ and $\boldsymbol{E}$ = 11 p per $\mathrm{kWh_e}$. Note that if, due to high values of $\boldsymbol{E}$, $\boldsymbol{V_T}$ falls below zero for any temperature above $\boldsymbol{T_0}$, $\boldsymbol{V_T}$ should be set to zero for that increment (for example, in Figure 3, when **E** = 25 p per $\mathrm{kWh_e}$, $\boldsymbol{V_T}$ reaches zero at just below 15°C; thus, for increments below 15°C, $\boldsymbol{V_T}$ is set to 0).

In its general form, the value of 1 tonne water at temperature $\boldsymbol{T}$ = $\sum_{i=T_0+1}^{T} V_i \times 1K \times c$ [4]

For comparison, 1 tonne of water at 40°C has a value of 2.85 GBP (Figure 3).

The practical implications of this (Figure 3) are:

1) When electricity is cheap, the value of geothermal fluid increases approximately linearly with temperature (and thus with depth, assuming a linear geothermal gradient).
2) As electricity prices increase, the relative value of geothermal fluids at lower temperatures decreases, the curve becomes more non-linear in character and there is greater economic motivation for exploring deeper (hotter) geological reservoirs.

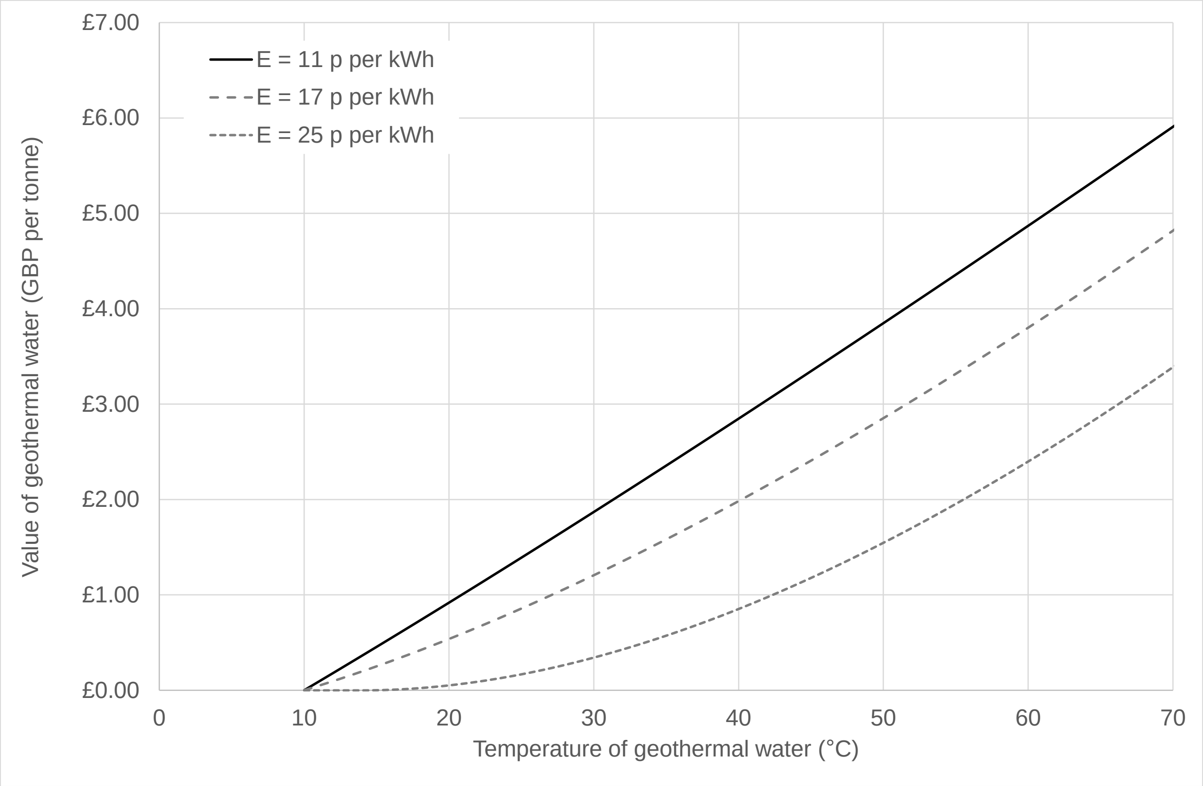

Figure 3. Value of 1 tonne of water at various temperatures and assuming varying electricity prices, V_{ref} = 9 p per kWh$_{th}$ at T_{ref} = 70°C and ε = 0.45. The diagram (arbitrarily) assumes a baseline of T_0 = 10°C, below which heat cannot be extracted efficiently. In this figure, when **E** = 25 p per kWh$_e$, V_T falls reaches zero at just below 15°C (Figure 2); thus, for increments below 15°C, V_T is set at 0 and T_0 effectively becomes c. 15°C.

Approach 2: A Theoretical Exergy-based Approach

The value of a warm geothermal fluid should be in some way related to its utility. As exergy is a direct measure of the ability of the fluid to do useful work (Bodvarsson and Eggers, 1972; Falcone et al., 2013; Lee, 2001; Rant, 1956), exergy can be taken as a proxy of value. According to (Shukaya and Hammache, 2002), the physical exergy (B_{ph}) of a fluid of constant specific heat capacity c and (absolute) temperature T^* at constant ambient pressure can be taken to be:

$$B_{ph} = c \times \left[(T^* - T_S^*) - T_S^* ln\left(\frac{T^*}{T_S^*}\right) \right] \qquad [5]$$

where T^*_s is the (absolute) reference temperature of the surroundings (i.e. a baseline or exhaust temperature). A value of c in kJ/kg/K gives an exergy value in kJ/kg.−

If we set $\boldsymbol{T^*_s}$ to 283.15K (10°C, corresponding with the baseline temperature in Approach 1) above, then we calculate a curve (Figure 4) whose shape resembles that derived from Approach 1.

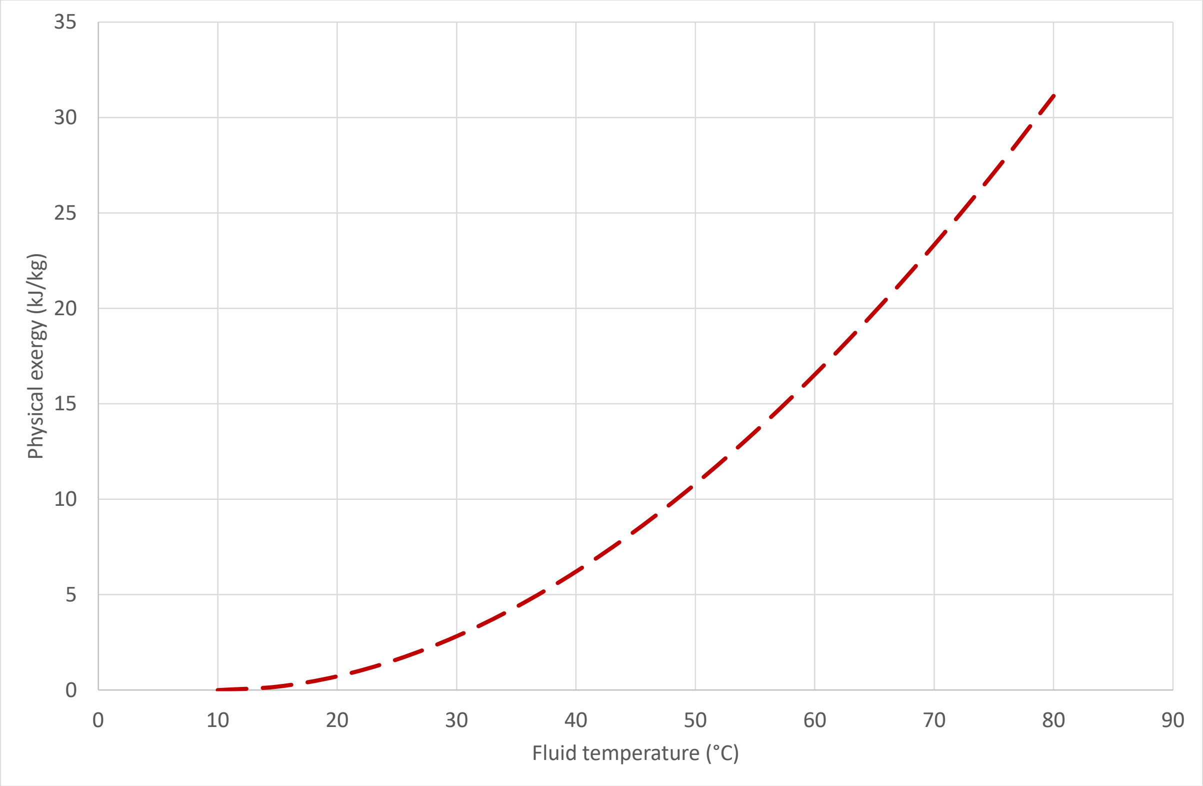

Figure 4. The physical exergy content of a warm fluid (kJ/kg) relative to a surrounding temperature of 10°C and at ambient pressure.

Dincer and Rosen (2021) argue that, as electricity is can be used for a wide variety of purposes and can be readily converted to work, the value of exergy is approximately equal to the price of electricity. If we set the exergy value to $\boldsymbol{E}$ = 11 p per kWh_e, then the comparative plot in Figure 5 can be derived. The plot compares the exergy value (Approach 2) with the heat pump discounting method (Approach 1) and also the costs of simply heating 1 tonne of water from 10°C using an electric resistance heater (assumed 100% efficient) and a combi-gas boiler (assumed 85% efficient).

Note that the value of geothermal water, based on a district heating price of 9 p per kWh_{th}, is similar to the cost of using gas to heat water, suggesting that district heating prices may be restrained by the cost of domestic gas boilers (i.e. the main potential competing household heating source). The graph also indicates why electrical resistance heating for space heating is usually regarded as economically unattractive in the UK.

Dincer and Rosen (2021) calculated that the price of exergy embedded in Swedish district heating systems is over 4 times the cost of pure exergy (valued by electricity prices). Intriguingly, this phenomenon is also found in Figure 5, when comparing the practical value of warm water (based on Approach 1 and founded in district heating prices) with the fundamental exergy value of warm water (Approach 2; based on electricity costs). This difference highlights the exergy inefficiency of using “exergy-dense” energy (hydrocarbons or electricity) to provide space heating or district heating, and the potential exergy efficiency of using heat pumps coupled to “low exergy” environmental heat sources for the same purpose.

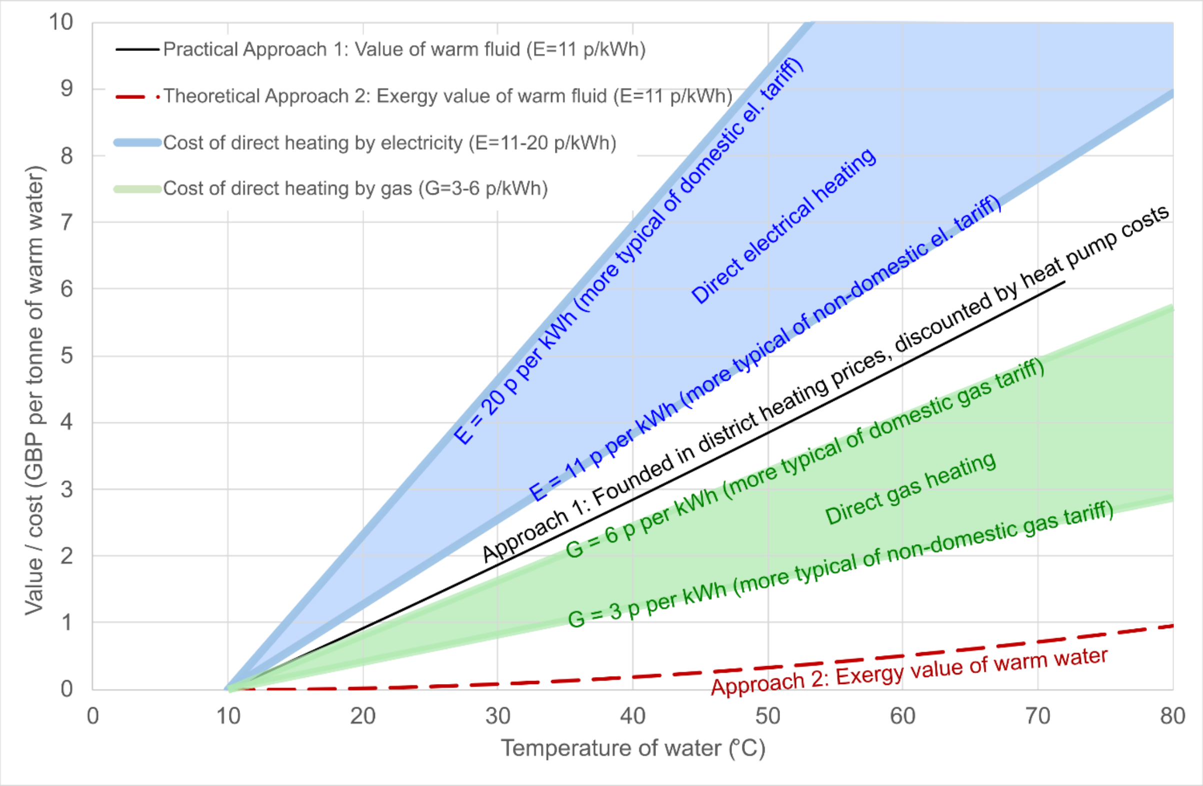

Figure 5. Value of warm water (e.g. geothermal water) per tonne, based on (1) Approach 1: heat pump discounting of district heating prices ($\boldsymbol{V_{ref}}$ = 9 p per kWh_{th} at $\boldsymbol{T_{ref}}$ = 70°C, ***E*** = 11 p per kWh_{e}) and (2) Approach 2: Value of exergy content (***E*** = 11 p per kWh_{e}). This is compared with the cost of warming water to the target temperature by (3) electrical resistance heating (***E*** = 11 to 20 p per kWh_{e}, 100% efficient) and (4) gas combustion (***G*** = 3 to 6 p per kWh, 85 % efficient). In all cases, the baseline temperature is 10°C.

Assumptions in these Approaches:

1. That a geothermal fluid of temperature $\boldsymbol{T_{ref}}$ can support a district heat network supplying heat at $\boldsymbol{T_{ref}}$ (Approach 1). In reality, there will be a temperature drop between the geothermal fluid and the network supply temperature, due to inefficiency of heat

exchange, and there will also be temperature losses elsewhere in the system (upward flow in the borehole, throughout the supply network).

2. No account is taken of the energy or economic cost of pumping geothermal fluid to the surface or circulation within a DHN (Approach 1), nor indeed of other capital investment in a well or other geothermal infrastructure. We argue that these costs should not be included in an approach that aims at comparing the values of water-based fluids at different temperatures (irrespective of source), as they are technology-specific.
3. The cost of running a heat pump is assumed to be solely the electrical cost of running the compressor. Maintenance, circulation pumping and capital costs are neglected, but could, in theory, be included (Approach 1).
4. The specific heat capacity ***c*** of the fluid is assumed to be constant with temperature, and salinity effects are neglected (Approaches 1 and 2). These could be incorporated to the calculation, if necessary.
5. That the COP of a real heat pump is assumed to be 45% of the ideal Carnot efficiency (Approach 1, see Abbreviations). This means that the COP to raise the temperature from 40°C to 70°C will be about 5.1, and to raise the temperature from 10°C it will be 2.6. In reality the COP will depend on many factors including the ΔT across the evaporator and the condenser and the flow rate.
6. The impact of water quality on value is not considered. For example, a highly corrosive or iron-rich water could be detrimental to value (risk of corrosion or scaling of heat pump or heat exchanger), while the presence of a valuable solute (such as lithium or natural gas; EGEC, 2020) that could be co-produced would enhance the value.

Conclusions

A practical method for valuing warm geothermal fluids (or, indeed, any warm fluid) is presented as Approach 1. It is founded in market values (V_{ref}) for provision of relatively high temperature (T_{ref}) waterborne district heating, discounted by the amount and value of electrical energy that must be consumed by heat pumps to transfer heat from the source fluid to the reference temperature and value.

The value of the warm geothermal fluid (in this approach) will depend on four factors:

- The market value of district heating (V_{ref}). This will often be tied to the cost of the main domestic alternative (e.g. gas combi-boilers) and may also be subsidised to cover the capital cost of installation. The absolute value selected for this parameter will control the value V_T calculated for a warm fluid at any temperature ***T*,** but it is the ratio between the electricity price ***E*** and $\boldsymbol{V_{ref}}$ that will control the shape of curves of value versus fluid temperature (Figures 2 and 3).

- The price of electricity (***E***) available to large non-domestic consumers (e.g. operators of DHN) to power heat pumps.
- The baseline temperature ($\boldsymbol{T_0}$) at which warm fluid is assumed to have no utility or value as a thermal resource.
- The efficiency of the heat pump ($\boldsymbol{COP_T}$).

At present, electricity prices are highly unstable. When electricity future prices are low, the relationship between warm water value and temperature is relatively linear. As the geothermal gradient is often linear, there are few gains to be made by drilling deeper. It may be more economically favourable to drill shallow boreholes to access cool, near-surface groundwater (c. 10-20°C), and use heat pumps to extract low temperature heat to support higher temperature space- or district heating. Such a strategy would also be encouraged by expensive drilling costs and by a high rate of increasing drilling costs per m with depth (Lukawski et al., 2014). Increased heat pump efficiency would also favour shallow geothermal sources.

However, let us suppose that electricity prices (***E***) increase relative to the price that consumers are willing to pay for supply of waterborne heat ($\boldsymbol{V_{ref}}$). In this case, the relative value of cool geothermal fluids falls and the non-linearity (downwardly convex curvature) of the relationship in Figure 3 becomes increasingly pronounced. In other words, drilling deeper to access hotter warm geothermal fluid becomes increasingly attractive, relative to cool surficial environmental heat sources. At the time of writing (OFGEM, 2022) electricity prices seem to be heading the direction of 50 p per kWh_e which, if sustained, would be a major driver for deep geo-/hydrothermal exploration for direct use.

We conclude that two main factors promote deeper exploration and exploitation for geothermal heat: (1) rising electricity prices (relative to the price that consumers are willing to pay for waterborne heat), (2) decreasing drilling costs.

This paper has also explored a second technique for valuing warm fluids, simply based on the value of the exergy contained in the fluid. This approach (Approach 2) results in very low – though theoretically sound – valuations. The fact that valuations using Approach 2 are so much lower than Approach 1 suggests three hypotheses:

- That district heating prices are not directly related to the exergy (utility) content of the fluids supplied, but are rather restrained by the cost of competing domestic heat sources.

- That the cost of district heating is likely to be dominated by capital costs (e.g. pipe-laying) rather than fuel, exergy or running costs.
- That conventional provision of district heating is still likely to be highly exergy inefficient, with exergy being wasted by the inefficient conversion of combustible fuels to heat (rather than work).

It is perhaps instructive to compare the calculated value of 1 tonne (1 m^3) of geothermal water at 70°C - 5.91 GBP – with the value of crude oil. Brent crude oil in the mid-2010s varied between c. 40 and c. 100 USD per barrel (252 to 629 USD per m^3). This dramatic difference in value emphasises the difficulties in economically transferring oil industry exploration and drilling techniques to the deep geothermal sector (Augustine, 2017).

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Glossary

4th Generation District Heating Network: a highly insulated, low temperature (<60-70°C) district heating network, designed to serve energy-efficient buildings via smart thermal grids, incorporating a number of different heat sources and thermal stores. Heat pumps are likely to be utilised. Low temperature distribution reduces thermal losses (Lund et al., 2014; Thorsen et al., 2018).

5th Generation District Heating Network: a largely decentralised district heating/cooling network operating around ambient temperatures (<25-30°C), to minimise thermal losses. Heat pump technologies are integral to such networks, transferring heat to and from consumers of heating and cooling at the required temperature. Thermal stores will be widely used for buffering purposes. Such networks perform especially well where heating and cooling loads are approximately balanced (Boesten et al., 2019).

Abbreviations

B_{ph} = the physical exergy content of a warm fluid (kJ/kg).

c = specific heat capacity of the fluid. We have assumed the geothermal fluid is fresh water with a constant specific heat capacity of 4.18 kJ/kg/K = 4.18 MJ/tonne/K = 1.161 kWh_{th}/tonne/K.

COP_T = coefficient of performance of heat pump in heating mode (dimensionless), at evaporator temperature T and condenser temperature T_{ref}.

ΔT = temperature differential between two fluid flows or two environmental “compartments”; for example, a temperature differential between fluids entering and exiting a heat exchanger.

DHN = district heating network

ε = ratio of real heat pump COP to ideal Carnot COP. The Carnot efficiency of a heat pump operating between 0°C (273K)and 35°C (308K) is 8.8, real heat pumps often do not achieve a COP great than 4 under such conditions – we have (somewhat arbitrarily) set ε = 0.45 in this paper.

E = price of electricity (GBP per kWh_e). For non-domestic customers this was around 11 p per kWh_e in the mid-late 2010s. Recent domestic tariffs are significantly higher.

EUR = 1 Euro.

G = price of mains gas supply (GBP per kWh). For non-domestic customers this was around 3 p per kWh in the mid-2010s. Recent domestic tariffs are significantly higher.

GBP = British pound. 100 p = 1 GBP.

kWh = kilowatt-hour. This is an amount of energy equivalent to an energy transfer or supply rate of 1 kW for 1 hr. A kilowatt-hour can refer to any type of energy, including thermal energy (kWh_{th}) and electrical energy (kWh_e). 1 kWh = 3.6 MJ.

T = temperature of geothermal water (K or °C)

T^* = asterisk denotes absolute temperature (K)

T_0 = baseline temperature at which geothermal fluid is deemed to have no utility and where value is zero (K or °C).

T_s = temperature of surroundings in an exergy calculations. This is effectively also a baseline temperature (K or °C) at which exergy value is zero.

T_{ref} = reference temperature of heat supply to consumer, e.g. in a DHN. (K or °C).

USD = US dollar. 100 ¢ = 1 USD.

V_T = value of geothermal waterborne heat at temperature T (GBP per kWh_{th})

V_{ref} = value or price of heat supplied to consumer at temperature T_{ref} (GBP per kWh_{th})