An analysis of the performance of the Erda borehole heat exchange system

Professor Alex Rogers
Department of Computer Science
University of Oxford, Oxford, UK
Email: alex.rogers@cs.ox.ac.uk

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This report reviews the thermal performance of the Erda borehole heat exchange system, comparing it against a counterfactual setting in which the equivalent heat is provided by a gas boiler. The report describes the methodology by which various performance metrics, such as the system carbon content (expressed in terms of the grams of CO_2 emitted for each kilowatt-hour of thermal energy delivered) and the coefficient of performance (expressed as the ratio of the heat provided to the electrical energy consumed), are calculated. This methodology incorporates the calculation of the real-time carbon intensity of the UK electricity grid, comparing this against standard values for the efficiency and carbon intensity of the counterfactual gas boiler. Using data from a test site from June 2016 to May 2017, the Erda system is shown to exhibit an average heat pump coefficient of performance of 4.3 and a system carbon content of just 75 gCO2/kWh. This contrasts with a system carbon content for the counterfactual gas boiler of 227 gCO2/kWh; exhibiting a 67% reduction in system carbon content, and a 81% reduction in primary energy input.

1 Introduction

The Erda borehole heat exchange system is a ground-coupled heat exchange system that uses of an array of boreholes, connected to a number of surface heat pumps, to provide both heating and refrigeration services to commercial buildings such as supermarkets. This report reviews the thermal performance of the Erda borehole thermal system, comparing the efficiency with which heating services are provided against a counterfactual setting in which the equivalent thermal energy is provided by a gas boiler. The report presents and validates the methodology by which a number of performance metrics are calculated to ensure that they are true and fair. It then applies this methodology to a test site using data from June 2016 to May 2017.

2 Methodology

The performance metrics considered here are based on measurements, made at five minute intervals, of the electrical energy consumed by the installed heat pumps and circulating fluid pumps, and of the thermal energy that is delivered. These measurements are combined with live UK electricity grid carbon intensity data, as described in more detail below, to calculate the carbon content of this delivered heat.

2.1 Typical Installation

Figure 1 shows a schematic of a typical installation where two main pumps, P1 and P2, circulate a fluid composed of a mixture of water and glycol around a main loop. Situated on this main loop is the borehole array. A typical installation may use between 10 and 20 boreholes, each approximately 200m deep; often inclined away from the initial surface footprint to maximise the subsurface volume accessed. Each borehole contains a steel casing, cemented in place by a thermally conductive grout. The circulating fluid passes down the borehole through a plastic tube, centred within the casing, and returns to the surface through the annulus between the tubing and the casing.

Three heat pumps connected into this main loop provide thermal energy to the domestic hot water system via a hot water tank, and to the heating system via an air handling unit. Three additional pumps, P5a, P5b and P6, circulate fluid on the condenser-side of these heat pumps independently of the fluid circulating in

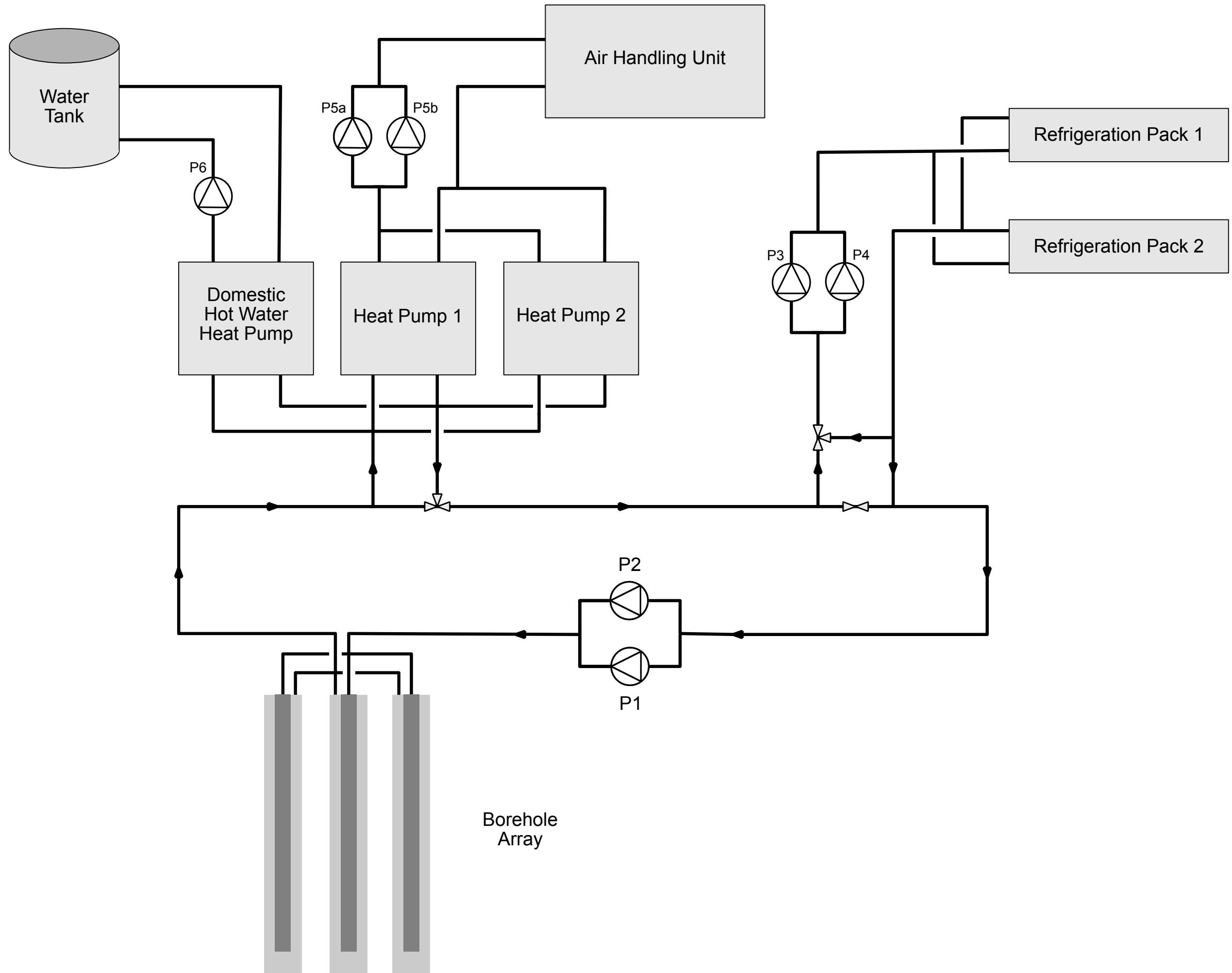

Figure 1: Diagram showing a typical installation supporting both heating and refrigeration services.

the main loop. An additional refrigeration circuit provides circulating fluid to two refrigeration packs, with additional pumps, P3 and P4, dedicated to circulating fluid through this sub-circuit.

Control valves allow the flow through the heat pumps, and through the refrigeration packs, to be automatically controlled. In particular, the refrigeration sub-circuit can be automatically and variably isolated from main loop in order to optimise the temperature of the circulating fluid entering the refrigeration packs.

Finally, the temperature and flow-rate of the circulating fluid is measured at a number of points within the circuit; both in the main loop and also in the loops taking heat from the heat pumps to the hot water tank, air handling unit, and refrigeration packs.

2.2 Calculation of Performance Metrics

The performance metrics considered in this evaluation compare the thermal performance of the Erda system to a counterfactual setting in which the equivalent heat is supplied by a gas boiler. Thus, in this counterfactual setting, we assume that the existing heating system, composed of the hot water tank and air handling unit is retained, but that the domestic hot water heat pump and the two heat pumps supplying the air handling unit are replaced by a gas boiler. Under this comparison, pumps P5a, P5b and P6 remain in place; as do the two refrigeration packs and associated pumps, P3 and P4, which operate as before, providing cooling services to the building. In addition, pumps P1 and P2 operate as before, circulating fluid within the main loop.

2.2.1 Thermal Energy Delivered

The thermal energy delivered by the heating system, Q_{thermal}, measured in kilowatt-hours in a given time period, ΔT, is given by the total thermal energy delivered to the domestic hot water system and the air handling unit by the three heat pumps. This is calculated from measurements of the temperature of the circulating fluid at the inlet and outlet of the condensing side of the heat pumps, the flow rate through the heat pumps on the condenser side, and the specific heat capacity of the circulating fluid.

2.2.2 Electrical Energy Consumed

The electrical energy consumed by the heating system, $W_{\text{electricity}}$, measured in kilowatt-hours over the same time period as above, is calculated from direct metering of the electricity consumption of the three heat pumps described above. Note that the energy consumed by pumps P1 and P2 circulating fluid in the main loop is shared by both the heating and refrigeration services in a proportion that is unknown. Thus, in this comparison, it is assumed that these electrical loads are solely consumed by refrigeration services and thus the calculations of the coefficient of performance and system carbon content reflect those of the heat pumps alone. Furthermore, note that the electrical consumption of the pumps that are retained in the counterfactual setting are ignored, as is the electricity consumption of the air handling unit and refrigeration packs themselves.

2.2.3 Coefficient of Performance and Renewable Energy Content

The coefficient of performance of the borehole thermal system is then simply calculated by the ratio of these two measured values:

$$COP = \frac{Q_{\text{thermal}}}{W_{\text{electricity}}} \tag{1}$$

In addition, the effective quantity of renewable heat that the system provides, $Q_{\text{renewable}}$, is calculated as the difference between the delivered heat and the electrical energy consumed:

$$Q_{\text{renewable}} = Q_{\text{thermal}} - W_{\text{electricity}} \tag{2}$$

2.2.4 Counterfactual Gas Consumption

The counterfactual case is calculated by considering that the Erda system has displaced a conventional gas boiler. Thus, the primary gas energy, Q_{gas}, that is required to deliver the same amount of heat as delivered by the Erda system is given by:

$$Q_{\text{gas}} = \frac{Q_{\text{thermal}}}{\eta_{\text{gas}}} \tag{3}$$

where η_{gas} is the efficiency of the gas boiler. This efficiency is taken to be 81% when considering the gross calorific value of the supplied natural gas. This is a standard value for the *boiler displacement method* when calculating emissions offset by a CHP plant (Department for Business, Energy & Industrial Strategy, 2016).

2.2.5 Primary Energy Saving

The resulting saving in primary energy, W_{saved}, can simply be expressed as the difference between the primary gas energy, Q_{gas}, that is required to deliver the same amount of thermal energy as delivered by the Erda system and the electrical energy consumed by the Erda system. This is given by:

$$W_{\text{saved}} = Q_{\text{gas}} - W_{\text{electricity}} \tag{4}$$

Table 1: *Carbon intensity of UK electricity sources.*

Source	Carbon Intensity gCO_2/kWh
Coal	937
Oil	935
Gas (Open Cycle)	651
Dutch Int.	474
Irish & East-West Int.	458
Gas (Closed Cycle)	394
Biomass	120
French Int.	53
Hydro	0
Nuclear	0
Pumped Storage	0
Solar	0
Wind	0

2.2.6 System Carbon Content

The system carbon content is calculated by considering the carbon intensity of the two primary energy sources: electricity in the case of the deployed borehole thermal system, and gas in the case of the counterfactual comparison system.

The carbon intensity of electricity is calculated by considering the instantaneous generation mix supplying the UK electricity grid. Instantaneous generation mix data is available from the balancing mechanism reporting service (BMRS) through a machine-readable API[1] and a human-readable website[2]. The carbon intensity of each unit of electricity generated is calculated by weighting the carbon intensity, ci, of each individual generation source, i, by how much its generation, g, contributes to the total:

$$CI_{\text{gen}} = \frac{\sum_{i=1}^{N} g_i \times ci_i}{\sum_{i=1}^{N} g_i} \tag{5}$$

There are a number of sources used for the carbon intensity of each individual source and a number of online sites use different figures. The values used here are shown in Table 1 and are taken from Staffell (2017) which represents the most up to date academic study of this issue.[3] In this table, the instantaneous generation mix category 'other' is labeled as 'biomass' since it

[1] `api.bmreports.com/BMRS/FUELINST/v1?APIKey=<APIKey>&ServiceType=xml`

[2] `www.bmreports.com/bmrs/?q=generation/fueltype`

[3] These figures are used in both the GridCarbon smartphone app (`www.gridcarbon.uk`) and the Drax Electric Insights website (`www.electricinsights.co.uk`).

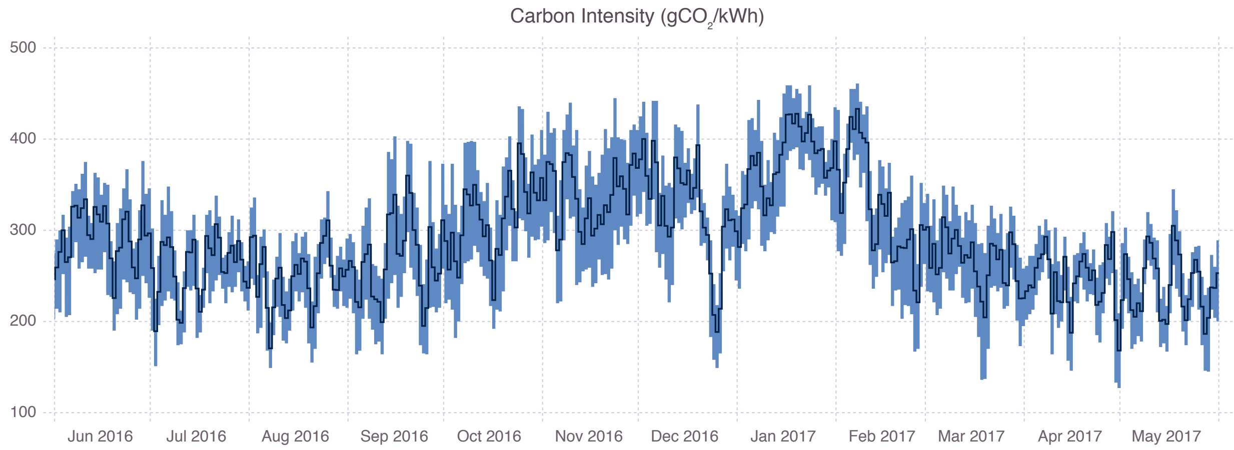

Figure 2: Daily minimum, average and maximum UK grid carbon intensity from June 2016 to May 2017.

now consists solely of coal-to-biomass conversions and biomass combined heat and power (CHP) plants. Note also that the electricity generated from pumped storage is assumed to be emission-free since the emissions are accounted for when the pumps consume electricity.

Since it is necessary to consider the carbon intensity of each unit of electricity that is consumed, as opposed to each unit of electricity that is generated, the losses in the transmission and distribution networks, l, must also be included. Thus, the carbon intensity of consumption is given by:

$$CI_{\text{grid}} = \frac{CI_{\text{gen}}}{1-l} \tag{6}$$

A value of 8% is used here for these losses, representing an average value between 1996 and 2015 (Department for Business, Energy & Industrial Strategy, 2016).

Figure 2 shows the daily minimum, average and maximum carbon intensity, calculated using this methodology, between June 2016 and May 2017. Note that there is significant daily, weekly and seasonal variation in the grid carbon intensity. The average carbon intensity over this period is 291 gCO_2/kWh.

The instantaneous generation mix data used above does not include un-metered generation from small-scale renewable sources deployed within the distribution network. Estimates of these additional renewable sources are available through an additional machine-readable API[4] and human-readable website[5]. However, this data is typically delayed by 1-2 hours[6] and is not used here. Embedded wind generation typically contributes an additional 30% to the figure for metered wind generation included within the instantaneous generation mix data. In addition, midday solar generation is now a significant contributor to the UK electricity grid with a maximum of 8020 MW observed on the 8th April 2017 throughout the period above.

Taken together, this means that the value of carbon intensity calculated here is slightly higher than other sources that includes embedded generation. Thus this represents a conservative estimate of carbon intensity. The discrepancy however is relatively small. Over the period between June 2016 and May 2017 the approach described here typically overestimates the carbon intensity by just 5%.

In addition to the carbon content of electricity, the carbon content of the counterfactual natural gas supply, CI_{gas} is required. A static figure of 184 gCO_2/kWh is used here as per the UK CHP Quality Assurance (CHPQA) programme (Department for Business, Energy & Industrial Strategy, 2016).

These values are then used to calculate the effective system carbon content expressed in terms of grams CO_2 emitted to deliver one kilowatt-hour of thermal energy:

$$SC_{\text{Erda}} = \frac{CI_{\text{grid}}}{COP} \tag{7}$$

Similarly, the system carbon intensity of the counterfactual gas boiler is given by:

$$SC_{\text{Gas Boiler}} = \frac{CI_{\text{gas}}}{\eta_{\text{gas}}} \tag{8}$$

Note that the system carbon content of the counterfactual gas boiler is fixed and reflects the guidance given in the UK CHPQA programme (Department for Business, Energy & Industrial Strategy, 2016), while that of the borehole thermal system varies with the changing coefficient of performance of the system and the changing carbon intensity of the electricity grid.

2.3 Example

Table 2 shows an example of this calculation for a 5 minute period in which, across multiple sites, 100 kWh of heat was delivered and 20 kWh of electricity was

[4] `api.bmreports.com/BMRS/B1630/v1?APIKey=<APIKey>&SettlementDate=<SettlementDate>&Period=<Period>&ServiceType=xml`

[5] www.bmreports.com/bmrs/?q=generation/

[6] See www.gridcarbon.uk for a fuller description of this issue.

Table 2: *Example system carbon content calculation.*

ΔT	5 min
Q_{thermal}	100 kWh
$W_{\text{electricity}}$	20 kWh
COP	5
$Q_{\text{renewable}}$	80 kWh
Q_{gas}	123 kWh
CI_{grid}	291 gCO_2/kWh
CI_{gas}	184 gCO_2/kWh
SC_{Erda}	58 gCO_2/kWh
$SC_{\text{Gas Boiler}}$	227 gCO_2/kWh

consumed. In this case, the average value for the carbon intensity of the electricity grid of 291 gCO_2/kWh is used, and the resulting system carbon content of the Erda system is calculated to be 58 gCO_2/kWh compared to 227 gCO_2/kWh for the counterfactual gas boiler; a reduction of 74%. In addition, the 123 kWh of primary gas consumption is reduced to 20 kWh of electricity consumption; a reduction of 84%. Note that these reductions are a function of the coefficient of performance of the borehole thermal system, COP, the efficiency of the counterfactual gas boiler, η_{gas}, and the carbon intensity of the UK natural gas and electricity supplies, CI_{gas} and $CI_{\text{electricity}}$.

2.4 Live and Aggregate Data

The calculation described above are appropriate when considering an individual time period. However, when the time period considered is short, it is also necessary to consider the thermal inertia of various components within the heating system. For example, for short periods after the heat pumps have been switched off, they will continue to provide heat as their internal components and the circulating fluid approach equilibrium, but they will consume zero electrical energy. In these cases, the system carbon content will go to zero and the coefficient of performance will go to infinity. Thus, when presenting performance metrics calculated over short time periods in a live system it is necessary to place lower and upper limits on the system carbon content and coefficient of performance displayed.

It is also commonly necessary to represent average values over extended time periods (such as a day, week, month or year). In this case, rather than averaging the values for the coefficient of performance and system carbon content calculated in each time period, it is necessary to calculate them by summing appropriately their input data. Thus, in this case, the average coefficient of performance is given by:

$$COP = \frac{\sum_{i=1}^{N} Q_{\text{thermal}}^{i}}{\sum_{i=1}^{N} W_{\text{electricity}}^{i}} \tag{9}$$

Similarly, the system carbon content of the Erda system is given by:

$$SC_{\text{Erda}} = \frac{\sum_{i=1}^{N} CI_{\text{grid}}^{i} \times W_{\text{electricity}}^{i}}{\sum_{i=1}^{N} Q_{\text{thermal}}^{i}} \tag{10}$$

where the total carbon emissions due to electricity consumption is calculated before being divided by the total heat delivered.

3 Application on Sample Data

Figure 3 shows the application of this methodology on data collected from a deployment site between June 2016 and May 2017. The plots show daily average values of the heat pump coefficient of performance and the system carbon content of both the Erda system and the counterfactual gas boiler. Over this period the average value of the coefficient of performance was 4.3 and the system carbon content was just 75 gCO2/kWh. This contrasts with a system carbon content for the counterfactual gas boiler of 227 gCO2/kWh; demonstrating a 67% reduction in system carbon content, and a 81% reduction in primary energy input.

Figure 4 shows annual averages of coefficient of performance and system carbon content, over a longer period, from January 2015 to May 2017. Note that each point on the graph represents the average over the preceding 12 month period, and thus, the average across the period show in Figure 3 is represented by the values at the extreme right of Figure 4. Across this period the annual coefficient of performance varies between 4.3 and 4.8, and the average system carbon content varies between 110 and 73 gCO_2/kWh. The variation in the coefficient of performance reflects changing weather conditions and operational use of the heating system. The variation in the system carbon content reflects the steady reduction in the carbon intensity of the UK electricity grid through increased deployment of low and zero carbon generation, and the retirement of older high-carbon generation sources.

4 Live Deployment

The methodology described above has been deployed to generate the performance figures displayed on the live Erda website. The cloud-based system collects UK electricity grid generation mix data every five minutes and combines this with live measurements of the flow rate and temperature of the circulating fluid, and measurements of electricity consumption of the heat pumps from each deployment site. The performance metrics described here are then calculated over this five minute period (with an upper bound on the coefficient of performance of 20) and also aggregated over longer periods (from one day to one month). The scripts used to generate and store this data have been

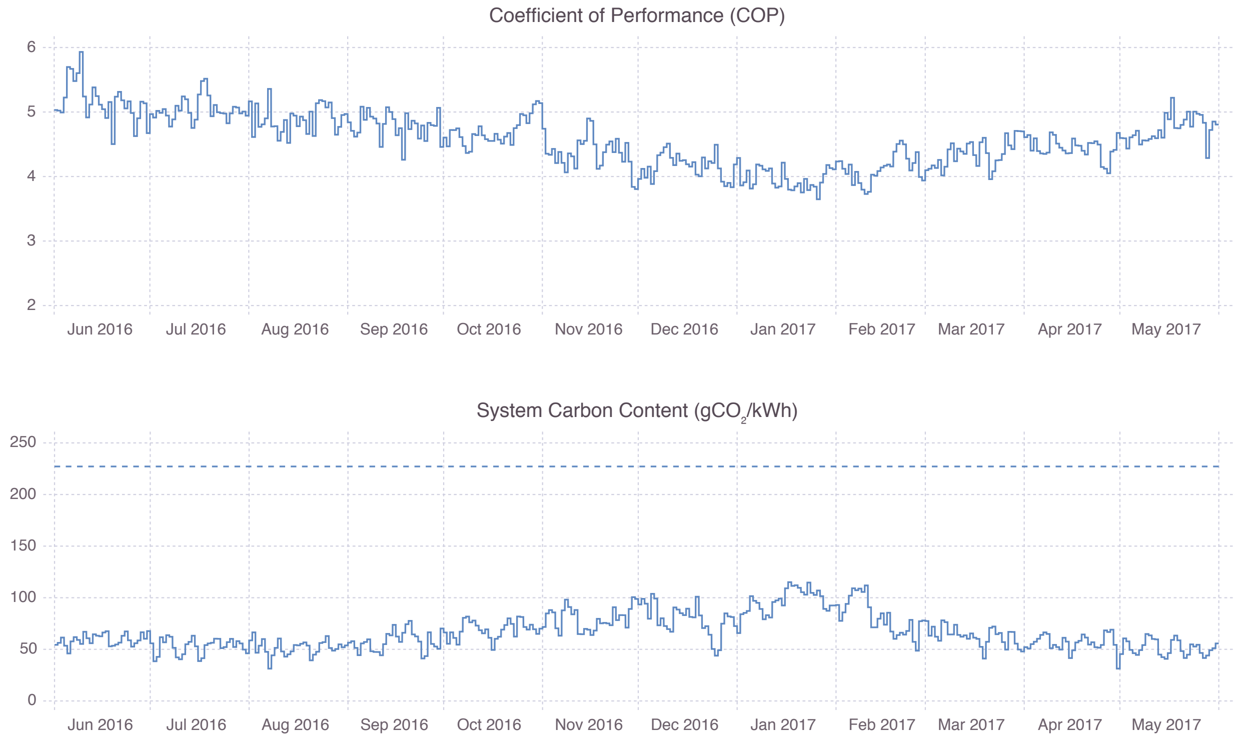

Figure 3: Coefficient of performance and system carbon content for Erda system (solid) and counterfactual gas boiler (dashed).

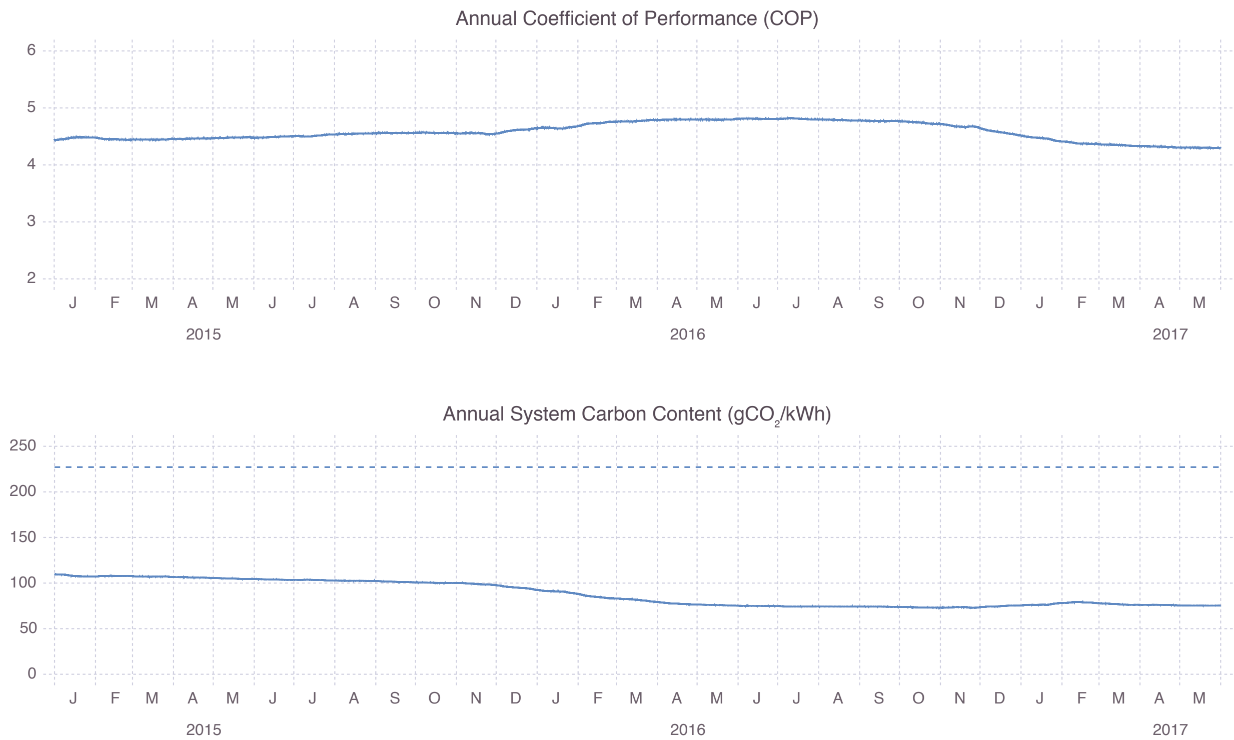

Figure 4: Coefficient of performance and system carbon content for Erda system (solid) and counterfactual gas boiler (dashed). Each point on the graph represents the average over the preceding 12 month period.

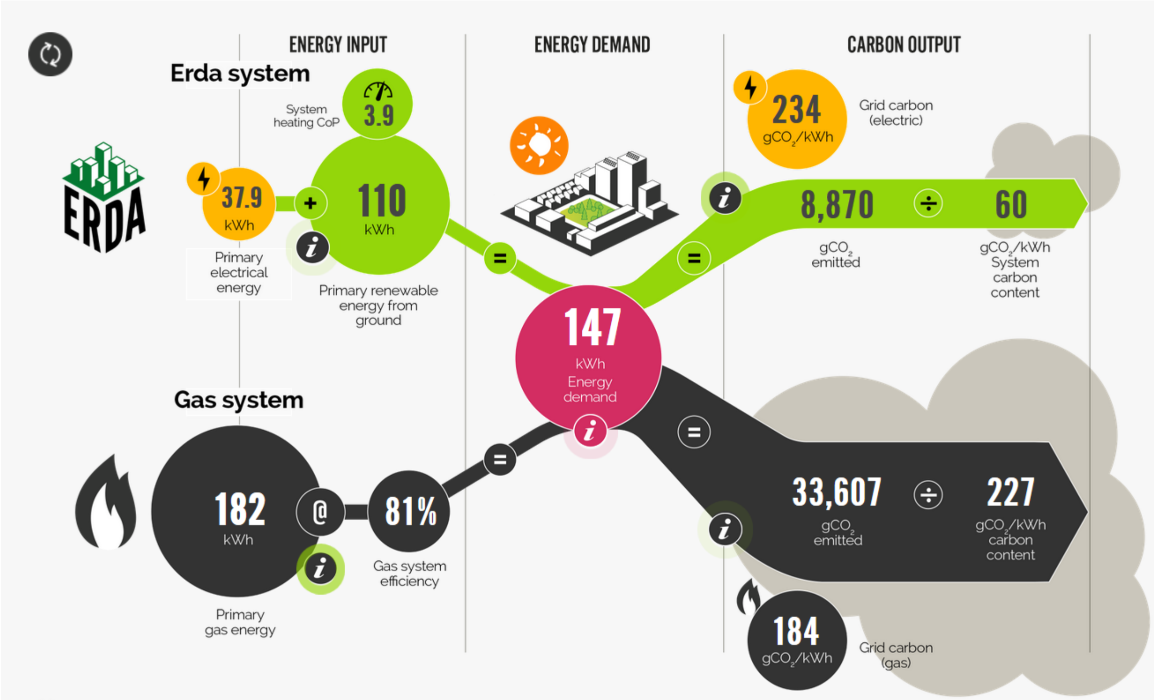

Figure 5: Information graphics used to illustrate calculation methodology with live data.

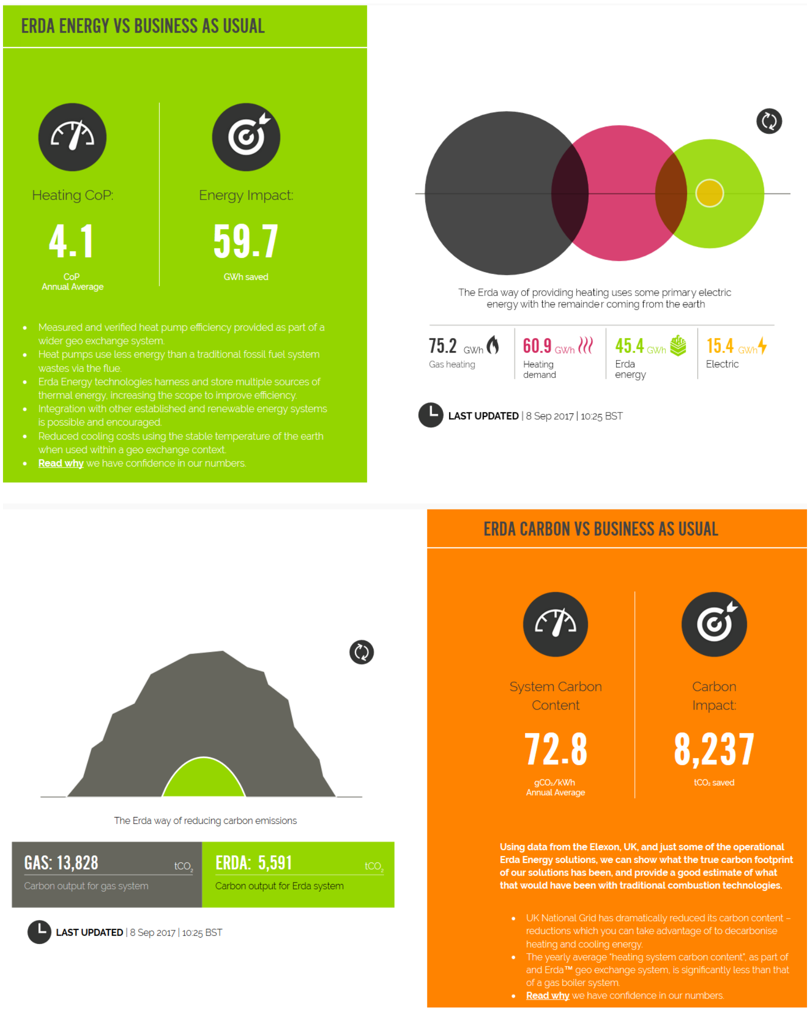

Figure 6: Information graphics used to display live and historical system performance metrics in context.

reviewed and audited to confirm that they conform to the description presented in this document.

Figures 5 and 6 show examples of the information graphics used to present this live and historical data on the website. Note that Figure 5 illustrates the methodology by which the performance metrics are calculated using live data and corresponds to the example shown in Table 2. Figure 6 shows two panels that put both live and historical data in context, showing the energy and carbon savings that have accrued over time, in addition to the live values of the coefficient of performance and system carbon content.

5 Conclusions and Future Work

This report presented and reviewed a methodology to compare the performance of the Erda borehole thermal system to a counterfactual setting where the equivalent heat was provided by a gas boiler. Using data from a test site from June 2016 to May 2017, the Erda system was shown to exhibit an average coefficient of performance of 4.3 and a system carbon content of just 75 gCO_2/kWh. This contrasts with a system carbon content for the counterfactual gas boiler of 227 gCO2/kWh; exhibiting a 67% reduction in system carbon content, and a 81% reduction in primary energy input. The system carbon content is expected to improve further as the carbon intensity of the UK electricity grid is reduced over time through increased deployment of low and zero carbon generation, and the retirement of older high-carbon generation sources. Indeed, the UK's legally binding carbon budget requires the carbon intensity of the UK electricity grid to be in the range of 50 - 100 gCO_2/kWh by 2030; a reduction by a factor of 3 - 6 compared to current values (Department of Energy & Climate Change, 2011).

The methodology as described is limited in two ways. First, it is constrained by the uncertainty in the attribution of the electrical energy consumption of pumps P1 and P2 that circulate fluid in the main loop. It was assumed these electrical loads are solely consumed by the refrigeration services, and thus, the calculation of the coefficient of performance and system carbon content reflects the performance of the heat pumps alone. Second, the methodology fails to quantify the improved operational efficiency of the refrigeration packs that is facilitated by their interaction with the heat pumps and the circulating fluid in the main loop. In particular, operating the two systems together allows low temperature circulating fluid from the evaporators of the heat pumps to be directed to the refrigeration packs; allowing them to operate in their most efficient operating regime for longer periods of time.

Since the energy consumed by pumps P1 and P2 is typically much less than that consumed by the heat pumps and the refrigeration packs, the effect of the first constraint is relatively small. Indeed, an equivalent analysis assuming that the electrical loads of pumps P1 and P2 are solely consumed by the heating services, leads to the coefficient of performance (and the system carbon content) being just 12% lower (and higher) than that presented in Figures 3 and 4

Thus, future work is directed to address the more significant tasks of estimating the improved thermal performance of the refrigeration services that results from operating them in parallel with the heat pumps and boreholes. Doing so is challenging. In the case of the heat pumps, it is relatively straightforward to calculate the thermal energy delivered, since the temperature change and flow rate can be measured across the condenser. In the case of the refrigeration packs, the circulating fluid typically also undergoes a state change as it passes through the evaporator, making direct economic measurement of heat extraction much more difficult. Thus, this work will likely include additional instrumentation of a small number of sites along with parallel operation of a conventional refrigeration system as a counterfactual. It is intended that this approach will develop a novel principled methodology to assess the impact of replacing conventional heating and refrigeration services with a more efficient integrated borehole heat exchange system.

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Biography

Alex Rogers is a Professor of Computer Science at the University of Oxford where his research addresses the use of data science, machine learning and artificial intelligence within future energy systems. He is the co-founder of Joulo (www.joulo.com); a University spin-out using low-cost USB temperature loggers and cloud-based intelligent algorithms to provide personalised home heating advise to individuals. Since 2009 he has developed and maintained the GridCarbon smartphone app (www.gridcarbon.uk) which provides real-time carbon intensity data for the UK electricity grid.