# Using BTES Technology to Decarbonise a Warehouse Space Heating System in the North East of England

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Summary:

The study considered the decarbonisation of warehouse space heating using a BTES system paired with flat-plate solar collectors, a ground source heat pump and fan coils. The replacement system's large capital costs mean it will not pay back within the project scope, and the cost of saved energy was too high. The replacement system is expected to cost the company a further £240,000 to £1.6m over the 20-year project scope compared to the conventional system, and the total discounted life-cycle costs of the replacement system are expected to be between 3.3x and 10x greater than the conventional.

2514 Words

## Technical Challenge

The workplace health, safety and welfare regulations of 1992 define the legal minimum temperature for a warehouse as 16 degrees Celsius [2]. However, due to often poor insulation, frequently open warehouse doors and high ceilings, a large heating capacity is required to quickly and effectively warm the space. The subject of this study is a warehouse situated in Stanley, County Durham, and is occupied by a steel fabrication company called Dyer Engineering. Its management team has provided real-world figures from an internal study conducted in 2017 on its heating system [3].

## Current solution

The warehouse is at present heated by five 80 kW industrial diesel-fired cabinet boilers with rated efficiencies of 92%, placed around the space close to workstations. Each boiler has an integrated electric heat circulation fan, and roof-mounted destratification fans recirculate the heat to ground level (fans will not be changed in decarbonised solution, so have not been included in the investigation), and the boilers run at maximum heating capacity when operational. Some salient numbers of the current system can be found in Table 1. These values are for a single 110m x 33m x 10m warehouse at their Harelaw facility, updated for the current price of diesel.

| | |
|---|---|
| System Heating Capacity | 400 kW |
| Diesel Boiler Efficiency | 92% |
| Total annual kWh delivered | 170,000 |
| £/kWh (average) | 0.14 |
| Total Annual Energy Cost (£) | 24,540 |
| Total Annual Running Time (hours) | 424.85 |

*Table 1 - Performance figures for the conventional diesel boiler system*

## Decarbonised Solution

Given the large amount of space available around the warehouse, the scale required and the lack of nearby flowing water, it was decided that a good potential solution was BTES technology, since it has the potential for commercial viability on a smaller scale [1]. The proposed system would use BTES, paired with flat-plate solar collectors, a short-term heat exchanger thermal storage tank and a ground source heat pump connected to a system of eight water-to-air fan coils distributed around the warehouse, as shown in Fig 1. During the summer months (1$^{st}$ April to 30$^{th}$ September), heat from the solar collectors is generated faster than the rate at which it can be transferred to the borehole system. The heat would therefore be stored in a short-term storage tank (buffer tank), and the GSHP would transfer this heat to the borehole storage system at a slower rate. This charging period was chosen as, outside of these six months, a steep reduction in irradiance is observed [39]. During the winter months, the heat pump would run through the day, transferring stored heat from the boreholes into the warehouse.

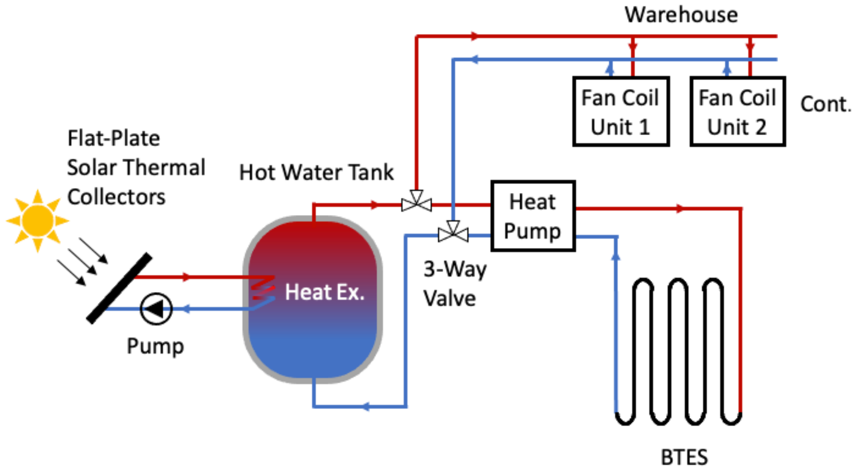



*Figure 1 - Schematic diagram of the proposed BTES warehouse heating system during borehole charging. During winter, the solar collectors are disconnected, and the system runs in the opposite sense.*

The Harelaw warehouse sits on a mix of sandy and stony clay down to 5.5m, followed by a bedrock of hard sandstone [27]. The potential borehole site is therefore assumed to be composed entirely of sandstone. No equipment is expected to have a positive salvage value.

Most Important Underlying Assumptions

| | | | | | |
|---|---|---|---|---|---|
| Discount rate | 0.10 | [4] | Efficiency of pipe, valves and tank (%) | 80% | |
| Project scope (Years) | 20 | | Collector Heat Removal Factor (Fr) | 0.6 | [23] |
| Prices and Tariffs | | | Transmission Coefficient of Glazing (τ) | 0.96 | [24] |
| RHI Tariff - Solar thermal (£/kWh) | 0.111 | [5] | Absorbtion coefficient of plate (α) | 0.95 | [24] |
| Electricity cost (£/kWh) | 0.16 | [6] | Fluid volume/m^2 solar collector (L/m^2) | 0.28 | [24] |
| UK diesel price (£/L) | 1.291 | [7] | Overall heat loss coefficient (W/m^2) | 1.2 | [25] |
| Propylene glycol price (£/L) | 5 | [8] | Annual collector yield (kWh/m^2) | 499 | [24] |
| Diesel (Current solution) | | | Inlet fluid temperature, Ti (°C) | 25 | [25] |
| Diesel boiler service life (years) | 20 | [9] | Outlet fluid temperature, To (°C) | 55 | [25] |
| 80kW diesel boiler unit cost (£) | 3,750 | [10] | Cost of solar collectors (£/m^2) | 400 | [26] |
| Diesel boiler rated efficiency (%) | 92% | [11] | **Borehole and Ground Properties** | | |
| Energy density of diesel (MJ/L) | 38 | [36] | Borehole service life (years) | 50 | [15] |
| Current drawn by fan (A) | 12 | [11] | Borehole thermal efficiency (%) | 33% | [1] |
| Voltage supply (V) | 230 | [11] | Installation cost per borehole (£) | 5000 | |
| BTES System | | | Vol. heat capacity of sandstone (MJ/m^3K) | 1.84 | [28] |
| % Propylene glycol in heat transfer fluid | 50 | [16] | Thermal conductivity of sandstone (W/mK) | 2.71 | [29] |
| **Ground Source Heat Pump** | | | **Heat Storage Tank** | | |
| Heat pump service life (yrs) | 20 | [19] | Heat storage tank service life (yrs) | 20 | [32] |
| 108.5kW GSHP single unit cost (£) | 42000 | [20] | Heat storage tank unit cost (£) | 9000 | [33] |
| Total installed capacity (kW) | 434 | [20] | Single unit volumetric capacity (m^3) | 22.7 | [33] |
| Heat pump CoP | 4.5 | [20] | Vol. heat capacity of water (MJ/m^3K) | 4.18 | [34] |
| Flat-Plate Solar Collectors | | | **Fan coils** | | |
| Heat transfer fluid service life (yrs) | 5 | [21] | 3-stage fan coil 50 kW unit cost (£) | 500 | [12] |
| Solar collector service life (yrs) | 25 | [22] | Fan coil expected service life (years) | 20 | [13] |

*Figure 2 - Key assumptions on which the analysis is based. Only assumed values have been provided. Value ranges are provided in the spreadsheet. Sources are listed in square brackets.*

Fig 2. shows only assumed values, but in some cases a range of uncertainty was provided. Energy delivered and running time will match those of the conventional diesel system (Table 1) [3]. A 10 % discount rate is typical for the industrial sector [4], and a 20-year scope was chosen as it is both the duration of Renewable Heat Incentive (RHI) tariff payments and the minimum expected lifespan of most system components.

***Prices and Tariffs***: Listed values were true as of 5/4/2021. The RHI tariff increases following the Consumer Price Index but has been treated as fixed for this analysis. The propylene glycol price is also fixed, as a change in its price would have little effect on overall costs. Electricity and diesel prices have the largest impact on project outcome, so a range has been provided for each, with maximum and minimum values estimated based on 10-year historical data.

***Diesel***: Unit price, rated efficiency and the distribution fan current and voltage figures are from the Powrmatic CPx 80kW diesel boiler [10] datasheet [11]. Diesel energy density varies, but 38 MJ/L is common for industrial diesel [36].

***BTES System:*** Heat transfer fluid must contain 50% propylene glycol to prevent freezing and solar collector damage [16]. Listed unit price, rated power and CoP are for the Dimplex 108.5 kW GSHP [20]. Four units will be cascaded for a total output of 434 kW. Unlike the boreholes, the solar collectors are an open system, and the heat transfer fluid must be replaced every five years [21]. A list of assumed solar collector values is provided, mostly obtained from the Barilla F22 datasheet [24]. An uncertainty range has been provided for the heat removal factor, the solar collector cost per $m^2$ and the inlet and outlet fluid temperatures, were based on values for existing systems [25]. The overall heat loss coefficient also varies but is assumed to be fixed as it has little effect on project outcome. An additional heat transfer efficiency of 80% has been included to account for additional pipe, valve and heat exchanger losses. Boreholes have an expected service life well beyond the project scope. At a low temperature and pressure, sandstone is porous and therefore the heat capacity is reduced. The assumed BTES efficiency of 33% is typical in the first year of operation [1]. This often rises with time, but usually stays below 50%. The largest available thermal storage tank was 22.7$\mathrm{m}^3$, so multiple tanks are required to store the daily heat generated by the collectors. The specific heat capacity of water was estimated based on the thermal operating range of the system (11°C to 55°C). The fan coil unit cost and power consumption are for the Reventon-50 [12].

Techno-Economic Model

## BTES System Technical Calculations

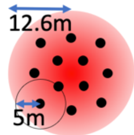



*Figure 3 - Borehole spacing*

***Number of boreholes***: The cylindrical volume of earth needed for thermal energy storage was found using (1). $Q_{tot}$ is the heat supplied by the system (MJ), $c_{v,sandstone}$ is the volumetric heat capacity of sandstone and $\eta_0$ is the borehole thermal efficiency. Annual temperature change $\Delta T$ was taken as 20°C. The cylinder radius was found using (2), where borehole depth $L$ = 100m. With 5m spacing [40], 12 boreholes were required (Fig. 3). Multiplying this by the cost per borehole and adding the heat transfer fluid cost gave the total borehole cost.

$$V_{earth} = \frac{Q_{tot}}{\eta_0 \times c_{v,sandstone} \times \Delta T} \quad (1)$$

$$r_{earth} = \sqrt{\pi \left( {V_{earth}}/{L} \right)} \quad (2)$$

***Thermal collectors surface area:*** This was found using the Hottel-Whillier-Bliss equation (3) [42]. $Q_u$ is the average required useful power over the charging period, $F_r$ is the heat removal factor, $I, \tau$ and $\alpha$ are the average daytime solar intensity, transmission coefficient of glazing and plate absorption coefficient, respectively. $U_L$ is the overall heat loss coefficient, $T_i$ is the average inlet fluid temperature and $T_a$ is the average ambient daytime temperature. Total cost was found using (4), where $C_{per\,m^2}$ is the cost per $m^2$ of collector (4).

$$A_{tot,tc} = \frac{Q_u}{F_r[I\tau\alpha - U_L(T_i - T_a)]} \quad (3)$$

$$C_{tot,tc} = C_{per\,m^2} \times A_{tot,tc} \quad (4)$$

***Heat storage tank capacity, $V_{water}$:*** The tank must be able to store the daily heat generated by the solar collectors. $Q_{avg,daily}$ is the average daily heat generated during the charging period (1 Apr – 30 Sept). Since this is a mean, a factor of safety of 1.5 was included to account for fluctuation. $c_{v,water}$ is the specific volumetric heat capacity of water. Assuming a $\Delta T$ of 44°C. (initially an ambient 11°C and heated to collector output temperature $T_o$ = 55°C), around 100 $m^3$ of water would be required, or five 22.73m$^3$ tanks.

$$V_{water} = \frac{1.5 \times Q_{avg,daily}}{c_{v,water} \times \Delta T} \quad (5)$$

***Heat transfer fluid replacement cost***: The volume of fluid in the solar collectors, $V_{coll}$, was calculated with (6). $V_{per\,m^2}$ is the fluid volume per $m^2$ of collectors and *A* is total collector area. The volume is multiplied by 1.05 to account for additional piping. Replacement cost $C_{rep}$ was found with (7). $\beta$ *is* the propylene glycol fraction and $C_{pg}$ is the propylene glycol price per litre.

$$V_{coll} = AV_{per\,m^2} \times 1.05 \quad (6)$$

$$C_{rep} = \beta C_{pg} V_{coll} \quad (7)$$

***Cost of electricity***: The power of one fan coil, $P_{coil}$, was multiplied by the total number of coils, *N*, the annual operating hours, T, and $C_{elec}$ to find the annual fan coil electricity cost. Annual GSHP electricity cost was found using (9), where $Q_{charge}$ and $Q_{discharge}$ are the heat supplied to the borehole during charging, and to the warehouse during discharging, respectively.

$$C_{elec,coils} = P_{coil} \times N \times T \times C_{elec} \quad (8)$$

$$C_{elec,GSHP} = \left( \frac{Q_{charge} + Q_{discharge}}{CoP} \right) C_{elec} \quad (9)$$

## Diesel Boiler Technical Calculations

Dividing the annual heat delivered, $Q_{tot}$ (MJ), by the boiler efficiency and diesel energy density, $U_{diesel}$ (MJ/L) gave the annual diesel consumption in L. This was multiplied by the diesel price per L, $C_{diesel}$, to find the annual diesel cost (10). Using (11), electricity cost for the distribution fans was found. $P_{fan}$ is the electrical power consumption of one boiler, *N* is the number of boilers, *T is* the annual operational hours.

$$C_{tot,diesel} = \frac{Q_{tot} \times C_{diesel}}{\eta_{boiler} \times U_{diesel}} \quad (10)$$

$$C_{elec,fans} = P_{fan} \times N \times T \times C_{elec} \quad (11)$$

## Economic Calculations

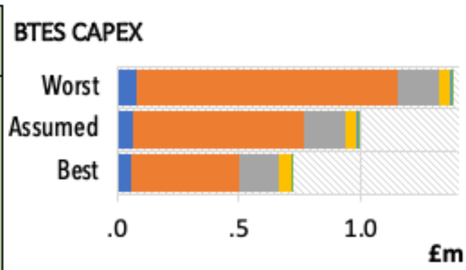
Best-case, assumed, and worst-case values for each economic indicator were found by using differing combinations of maximum, assumed and minimum values of OPEX, CAPEX and energy consumption. For the simple payback period, the denominator was calculated as: $Operational\ Savings = OPEX_{conv} + RHI\ Income - OPEX_{repl}$, and lost RHI earnings during construction were also accounted for. The best-case SPP assumed $CAPEX_{conv}$ and $OPEX_{conv}$ to be maximum and $CAPEX_{repl}$ and $OPEX_{repl}$ to be minimum. The LCOSE of the replacement compared to the conventional was calculated to factor in both electricity and fuel consumption. The diesel capacity factor is the ratio of actual delivered heat to delivered heat if the system ran at max capacity all year. The BTES CF is the ratio of annual heat delivered to maximum possible solar yield (kWh). Total life-cycle costs for each system were also calculated.

## Results

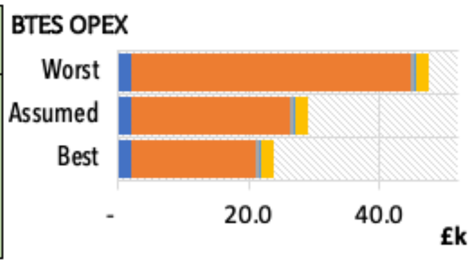
| | BTES System | | | Diesel (Conventional) | | |
|---|---|---|---|---|---|---|
| | Best-Case (min costs, max savings) | Assumed | Worst-Case (max costs, min savings) | Best-Case | Assumed | Worst-Case |
| Total CAPEX (£k) | 719.1 | 990.1 | 1,373.5 | 24.5 | 24.5 | 24.5 |
| Total OPEX (£k/yr) | 23.9 | 29.1 | 47.5 | 17.1 | 24.0 | 28.2 |
| RHI Earnings (£k/yr) | 18.9 | 18.9 | 18.9 | | | |
| Operational savings (£k/yr) | 23.2 | 13.8 | (11.5) | | | |
| LCOSE (£k/kWh) | 2.13 | 4.20 | 14.02 | | | |
| Capacity factor (%) | 23.1% | 19.4% | 15.9% | 4.5% | 4.5% | 4.5% |
| Payback period (yrs) | - | - | - | | | |
| Construction time (yrs) | 0.5 | 0.5 | 0.5 | | | |

*Figure 4 - Total CAPEX and OPEX of each system, RHI earnings, LCOSE of replacement system compared to the conventional, capacity factor and simple payback period. Best-case, assumed and worst-case scenarios are shown.*

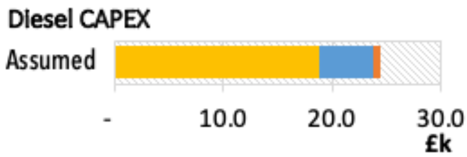
| **BTES System CAPEX (£)** | Best-Case (£k) | Assumed (£k) | Worst-Case (£k) | CAPEX (£k/kW) |
|---|---|---|---|---|
| Borehole installation | 55.9 | 67.9 | 79.9 | 0.16 |
| Thermal collectors | 441.9 | 700.9 | 1,072.3 | 1.61 |
| Heat pumps | 168.0 | 168.0 | 168.0 | 0.39 |
| Heat storage tank | 45.0 | 45.0 | 45.0 | 0.10 |
| Decommissioning (disc.) | 3.3 | 3.3 | 3.3 | 0.01 |
| Heat pump installation | 5.0 | 5.0 | 5.0 | |
| Total CAPEX | 719.1 | 990.1 | 1,373.5 | **2.28** |




| **BTES System OPEX (£/yr)** | Best-Case (£k) | Assumed (£k) | Worst-Case (£k) | OPEX (£k/kW) |
|---|---|---|---|---|
| Heat pump maint. | 2.0 | 2.0 | 2.0 | 0.00 |
| Elec. cost (GSHP+coils) | 19.1 | 24.3 | 42.7 | 0.06 |
| HT fluid replacement | 0.6 | 0.6 | 0.6 | 0.00 |
| Storage tank maint. | 0.2 | 0.2 | 0.2 | 0.00 |
| Solar collectors maint. | 2.0 | 2.0 | 2.0 | |
| Total OPEX | 23.9 | 29.1 | 47.5 | **0.07** |




| **Diesel System CAPEX (£)** | | Assumed (£k) | | CAPEX (£k/kW) |
|---|---|---|---|---|
| Cost of 5 diesel boilers | | 18.8 | | 0.05 |
| Installation cost | | 5.0 | | 0.01 |
| Decommissioning (disc.) | | 0.7 | | 0.00 |
| Total CAPEX | | 24.5 | | **0.06** |




| **Diesel System OPEX (£/yr)** | Best-Case (£k) | Assumed (£k) | Worst-Case (£k) | OPEX (£/kW) |
|---|---|---|---|---|
| Total annual fuel cost | 15.8 | 22.6 | 26.3 | 0.05 |
| Maintenance cost | 0.5 | 0.5 | 0.5 | 0.00 |
| Elec. cost (fans) | 0.8 | 0.9 | 1.5 | 0.00 |
| Total OPEX | 17.1 | 24.0 | 28.2 | 0.55 |

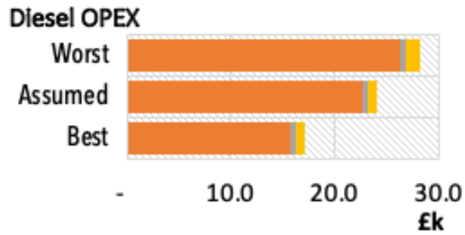



*Figure 5 - OPEX and CAPEX breakdowns for the BTES and conventional system. Best-case, assumed and worst-case scenarios are shown. The diesel CAPEX is small and values are not variable, so no range has been provided.*

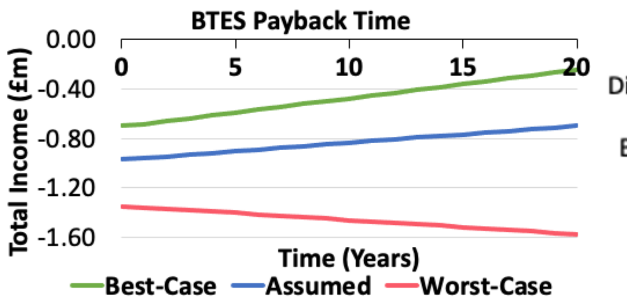



*Figure 6 - The range of potential simple payback for BTES.*

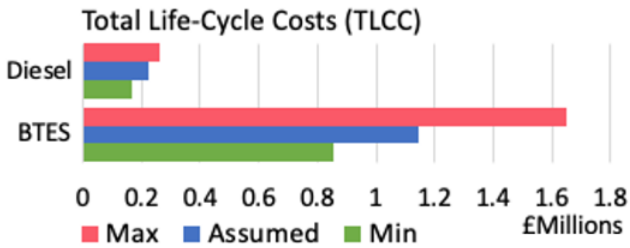



*Figure 7 - Total discounted life-cycle costs for each system, assuming a 10% discount rate*

Analysis and Discussion

No payback was seen in the BTES system due to high capital costs, primarily driven by the cost of thermal collectors (expected to account for 60-80% of capital expenditure), as well as the need to run during summer to recharge the boreholes, and the low borehole thermal efficiency requiring high solar collector capacity. Fig. 6 shows that in the best-case scenario if diesel prices remained high throughout the period, electricity prices remained low and capital costs were reduced by lower-than-expected total borehole and solar collector installation costs, this system would still cost the company £200,000 more over the 20-year scope than if it remained with the current system. In the worst-case scenario, the BTES system could have higher operational costs than the conventional diesel system, even after deducting the almost £19,000 in annual RHI tariffs. However, the BTES system could be viable in more northern climates, as GSHP efficiency is less affected by cold weather than other decarbonised solutions, such as ASHPs. The diesel system had a discounted TLCC of between £170,000 £260,000 (Fig. 7). In contrast, BTES had a much greater TLCC of between 860,000 and £1.65 million, with the most reasonable estimate being £1.15 million, or between 3.3x and 10x greater than the conventional. Additionally, the reduction in discounted lifetime energy consumption of the BTES system compared to the diesel system is quite small (1.16-1.45 GW for BTES vs. 1.58 GW for diesel). These two factors, when put together, mean the BTES system has a very high LCOSE, seen in Fig. 4. When applying a 10% discount rate, each kWh of lifecycle energy savings is estimated to cost anywhere from £2.13 all the way up to £14.02, with an assumed cost of £4.20/kWh. These values are far too large to be feasible [41]. Although the BTES system has a higher capacity factor than the conventional system, the CAPEX and OPEX per installed kW are much greater, meaning it is not financially viable. This is because as well as being inexpensive to purchase, the diesel boilers only run during winter, and their fuel and electricity costs are zero when not in use. The variation in the BTES capacity factor (Fig. 4) was due to uncertainties in solar collector area.

There are additional limitations in the BTES system. Drilling rigs are scarce and in the event of an upswing in the construction sector the sourcing of a rig to a small site such as Harelaw would be very difficult. Stanley is a former mining region, so there is a risk of encountering existing structures during drilling, such as mineshafts, as well as unconsolidated regions of sandstone which could collapse and cause damage to the drill or the heating loop [43]. This, in conjunction with the complexity of the system means the construction period could span up to six months, during which the diesel system would continue to operate, reducing total operational savings within the project scope. The GSHP would also be unable to cool the warehouse during summer, as it would be occupied with borehole recharging. The system's complexity increases the likelihood of a component failure, which could lead to downtime and maintenance costs. BTES relies on the borehole storing at least 33% of the heat that is charged into it. This can vary a lot, and during in the early years backup fuel-burning heaters could be required to compensate, increasing the CAPEX.

The best-case and worst-case scenarios are based on fluctuations in prices and capital expenditure that are unlikely to occur in reality, especially not all at the same time. The likelihood that real figures would fall within these ranges is therefore high. The two most uncertain values are the borehole and solar collector capital costs, which were based on similar sized projects. However, it was sometimes uncertain exactly what costs were included in these price estimations. There was also uncertainty when estimating maintenance costs for each system, but Fig. 5 reveals these costs to have a minor impact on OPEX compared to fuel and electricity costs. Discounted payback period was not used in this analysis as it doesn't account for returns after payback [13]. Fluid replacement cost was annualised and included in the OPEX, and component decommissioning costs were discounted and included in CAPEX. All components except the boreholes are assumed to be decommissioned at the end of the project scope. Note that the GSHPs had a capacity greater than the 400 kW required, as it is difficult to find units with exactly correct outputs. This resulted in a slightly elevated CAPEX.

References

[1] gov.uk.
2021. *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1_.pdf*. [online] Available at: <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1_.pdf> [Accessed 30 April 2021].

[2] Great Britain: Health And Safety Executive, 1992. *Workplace (health, safety and welfare) regulations 1992 - approved code of Conduct*. 2nd ed.

[3] Larder, R., 2017. Dyer Engineering. Replacing the Harelaw Warehouse Diesel Heating System with Biofuel

[4] Short, W., Packey, D. and Holt, T., 1995. *A manual for the economic evaluation of energy efficiency and renewable energy technologies*. Honolulu, Hawaii: University Press of the Pacific.

[5] Ofgem. 2021. *Non-Domestic RHI tariff table*. [online] Available at: <https://www.ofgem.gov.uk/publications-and-updates/non-domestic-rhi-tariff-table> [Accessed 30 April 2021].

[6] GlobalPetrolPrices.com. 2021. *United Kingdom electricity prices | GlobalPetrolPrices.com*. [online] Available at: <https://www.globalpetrolprices.com/United-Kingdom/electricity_prices/> [Accessed 5 April 2021].

[7] GlobalPetrolPrices.com. 2021. *United Kingdom diesel prices, 5-Apr-2021 | GlobalPetrolPrices.com*. [online] Available at: <https://www.globalpetrolprices.com/United-Kingdom/diesel_prices/> [Accessed 5 April 2021].

[8] ReAgent Chemicals. 2021. *Monopropylene Glycol | Buy Mono Propylene Glycol | UK Suppliers*. [online] Available at: <https://www.chemicals.co.uk/monopropylene-glycol> [Accessed 5 April 2021].

[9] Plant Engineering. 2021. *Plant Engineering | Boiler retrofits extend service life*. [online] Available at: <https://www.plantengineering.com/articles/boiler-retrofits-extend-service-life/> [Accessed 30 April 2021].

[10] Warm Air Heaters - Oil And Gas Industrial, Commercial & Factory Warm Air Heating. 2021. *Powrmatic CPx 90kW Oil Fired Cabinet Heaters Low NOx High Efficiency*. [online] Available at: <https://www.warmairheaters.com/product/powrmatic-cpx-90kw-oil-cabinet-heater/> [Accessed 30 April 2021].

[11] CPx Gas & Oil Cabinet Heater Industrial & Commercial Heating Systems. 2021. [online] Available at: <https://d300e5me90gfs3.cloudfront.net/wp-content/uploads/2018/11/2018-ErP-Powrmatic-CPx-Trade-Brochure-5.5-2.pdf> [Accessed 30 April 2021].

[12] VPS Industrial Heating. 2021. *Fan Coil Unit Heater Steel Casing 50kW - VPS Industrial Heating*. [online] Available at: <https://www.vpsindustrialheating.co.uk/product/fan-coil-unit-heater-steel-casing-50kw/> [Accessed 30 April 2021].

[13] Certified Clean Air Corporation. 2021. *Fan Coil Units - Certified Clean Air Corporation*. [online] Available at: <https://certifiedcleanaircorp.com/fan-coil-

units/#:~:text=The%20average%20lifespan%20of%20a%20vertical%20fan%20coil,they%20will%20naturally%20age%2C%20degrade%2C%20and%20eventually%20fail> [Accessed 30 April 2021].

[14] 2021. *Technical documentation AIR WATER HEATERS IN STEEL CASING S SERIES*. [online] Available at: <https://www.vpsindustrialheating.co.uk/wp-content/uploads/2019/06/Technical-datasheet-air-water-heaters-Reventon-S-3S-series-01-2019.pdf> [Accessed 30 April 2021].

[15] Rubino, A., 2013. *Life Cycle Assessment of Underground Thermal Energy Storage Systems*. [online] Dspace.unive.it. Available at: <http://dspace.unive.it/bitstream/handle/10579/3476/836995-1167743.pdf?sequence=2> [Accessed 30 April 2021].

[16] Energy.gov. 2021. *Heat Transfer Fluids for Solar Water Heating Systems*. [online] Available at: <https://www.energy.gov/energysaver/solar-water-heaters/heat-transfer-fluids-solar-water-heating-systems> [Accessed 2 May 2021].

[17] Invernizzi, Diletta & Locatelli, Giorgio & Velenturf, Anne & Love, Peter & Purnell, Phil & Brookes, Naomi. (2020). Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning. Energy Policy. 144. 10.1016/j.enpol.2020.111677.

[18] Ofgem.gov.uk. 2021. *Easy Guide to the Non-Domestic RHI*. [online] Available at: <https://www.ofgem.gov.uk/system/files/docs/2021/04/easy_guide_to_ndrhi_final_2021_0.pdf> [Accessed 30 April 2021].

[19] The Renewable Energy Hub. 2021. *Heat Pump Maintenance*. [online] Available at: <https://www.renewableenergyhub.co.uk/main/heat-pumps-information/maintenance-of-heat-pumps/> [Accessed 30 April 2021].

[20] Dimplex.co.uk. 2021. *130kW Reversible Ground Source Heat Pump SI130TUR+*. [online] Available at: <https://www.dimplex.co.uk/product/130kw-reversible-ground-source-heat-pump-si130tur> [Accessed 30 April 2021].

[21] Energy.gov. 2021. *Heat Transfer Fluids for Solar Water Heating Systems*. [online] Available at: <https://www.energy.gov/energysaver/solar-water-heaters/heat-transfer-fluids-solar-water-heating-systems> [Accessed 30 April 2021].

[22] Fan, J, Chen, Z, Furbo, S, Perers, B & Karlsson, B 2009, Efficiency and lifetime of solar collectors for solar heating plants. in Proceedings of the 29th ISES Biennial Solar World Congress 2009, ISES 2009. vol. 1, Johannesburg, South Africa, pp. 331-340, 29th Biennial Solar World Congress of the International Solar Energy Society, Johannesburg, South Africa, 11/10/2009.

[23] Montoya-Márquez, Orlando & Flores-Prieto, José. (2018). Heat Removal Factor in Flat Plate Solar Collectors: Indoor Test Method. Energies. 11. 2783. 10.3390/en11102783.

[24] Barillasolar.co.uk. 2021. *Barilla Solar Collector F22 AR Datasheet*. [online] Available at: <http://www.barillasolar.co.uk/assets/download/index/assets/53/> [Accessed 30 April 2021].

[25] Handbook.ashrae.org. 2021. *CHAPTER 36 SOLAR ENERGY USE*. [online] Available at: <https://handbook.ashrae.org/Handbooks/A19/IP/A19_Ch36/a19_ch36_ip.aspx> [Accessed 30 April 2021].

[26] Mahjouri, F. and Nunez, A., 2004. The relative cost of solar thermal collector installations. [online] Available at: <http://www.thermomax.com/Downloads/Relative%20Cost%20Paper.pdf> [Accessed 30 April 2021].

[27] Scans.bgs.ac.uk. 2021. *Borehole NZ15SE406 | Borehole Logs*. [online] Available at: <http://scans.bgs.ac.uk/sobi_scans/boreholes/18134686/images/18133518.html> [Accessed 30 April 2021].

[28] Koňáková, Dana & Vejmelková, E. & Černý, Robert. (2013). Thermal properties of selected sandstones, Advances in Modern Mechanical Engineering, Dubrovnik. Croatia, Proceedings of FLUIDSHEAT'. 13. 100-104.

[29] Abdulagatova, Z. & Abdulagatov, Ilmutdin & Emirov, V.N. (2009). Effect of temperature and pressure on the thermal conductivity of sandstone. International Journal of Rock Mechanics and Mining Sciences. 46. 1055–1071. 10.1016/j.ijrmms.2009.04.011.

[30] Skarphagen, Helge & Banks, David & Frengstad, Bjørn & Gether, Harald. (2019). Design Considerations for Borehole Thermal Energy Storage (BTES): A Review with Emphasis on Convective Heat Transfer. Geofluids. 2019. 1-26. 10.1155/2019/4961781.

[31] Icax.co.uk. 2021. *Borehole Thermal Energy Storage BTES | Ground Source Drilling | Rechargeable Heat Battery | Heat storage | Heat Well | CFD | Thermal Energy Storage using Interseasonal Heat Stores*. [online] Available at: <https://icax.co.uk/Borehole_Thermal_Energy_Storage.html> [Accessed 30 April 2021].

[32] GSC Tanks. 2021. *An Introduction to Industrial Hot Water Storage Tanks*. [online] Available at: <https://www.gsctanks.com/industrial-hot-water-storage-tanks/> [Accessed 30 April 2021].

[33] SunMaxx Solar. 2021. *5000 Gallon Non-pressurized Buffer Tank - SunMaxx Solar*. [online] Available at: <https://www.sunmaxxsolar.com/product/5000-gallon-non-pressurized-buffer-tank/> [Accessed 30 April 2021].
[34] Engineeringtoolbox.com. 2021. *Water - Specific Heat Capacity*. [online] Available at: <https://www.engineeringtoolbox.com/specific-heat-capacity-water-d_660.html> [Accessed 30 April 2021].

[35] Thiao, Serigne & Mar, Awa & Diokh, Reine & Mbow, Cheikh & Youm, Issakha. (2018). Feasibility Study of a Solar Thermal Cooling Warehouse on a Remote Area: Estimation of the Solar Thermal Collector Area and Efficiency. International Journal on Energy Conversion (IRECON). 6. 90. 10.15866/irecon.v6i3.14289.

[36] Hypertextbook.com. 2021. *Energy Density of Diesel Fuel - The Physics Factbook*. [online] Available at: <https://hypertextbook.com/facts/2006/TatyanaNektalova.shtml> [Accessed 30 April 2021].

[37] World Weather & Climate Information. 2021. *Average monthly hours of sunshine in Durham (Durham), United Kingdom*. [online] Available at: <https://weather-and-climate.com/average-monthly-hours-Sunshine,durham-durham-gb,United-Kingdom> [Accessed 30 April 2021].

[38] climate-data.org. 2021. *DURHAM WEATHER AND TEMPERATURE AVERAGES BY MONTH*. [online] Available at: <https://en.climate-data.org/europe/united-kingdom/england/durham-95/> [Accessed 30 April 2021].

[39] Data.ceda.ac.uk. 2021. *MIDAS Open: UK hourly solar radiation data, v201901*. [online] Available at: <https://data.ceda.ac.uk/badc/ukmo-midas-open/data/uk-radiation-obs/dataset-version-201901/durham/00326_durham/qc-version-1> [Accessed 30 April 2021].

[40] Gehlin, S. (2016). Borehole thermal energy storage. 10.1016/B978-0-08-100311-4.00011-X.

[41] Ackerman, F., Knight, P. and Biewald, B., 2016. *Estimating the Cost of Saved Energy*. [online] Available at: <https://www.synapse-energy.com/sites/default/files/COSE-EIA-861-Database-66-017.pdf> [Accessed 30 April 2021].

[42] Struckmann, F., 2021. *Analysis of a Flat-plate Solar Collector*. [online] Available at: <https://www.lth.se/fileadmin/ht/Kurser/MVK160/Project_08/Fabio.pdf> [Accessed 30 April 2021].

[43] Aldred, W. *et al*., 1999. *Managing Drilling Risk*. [online] Available at: <https://www.slb.com/-/media/files/oilfield-review/manage> [Accessed 30 April 2021].