Decarbonising A Warehouse Space Heating System in the North East of England

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Summary:

The study compared two decarbonisation solutions for industrial space heating. 1) A BTES system paired with flat-plate solar collectors, a GSHP and fan coils. 2) An ASHP system paired with fan coils. The BTES system's large capital costs meant it would be very unlikely to pay back within the project scope, and the reduction in energy consumption was small. The ASHP system had much lower capital costs and led to significant energy and operational cost savings compared with the conventional system. It is expected to pay back in around seven years and save more than £400,000 over 20 years.

3442 Words

Technical Challenge

The workplace health, safety and welfare regulations of 1992 define the legal minimum temperature for a warehouse where strenuous activities aren't taking place 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. Their management team has provided real-world figures from an internal study conducted in 2017 on their heating system [3].

Current solution

The warehouse is at present heated by five 80 kW industrial diesel-fired cabinet boilers with rated efficiencies of 90%, placed around the space close to workstations. Roof-mounted destratification fans recirculate the heat to ground level (fans will not be changed in decarbonised solutions, 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	90%
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 Solutions

Given the large amount of space available around the warehouse, the scale required and the lack of nearby flowing water, it was decided that two potential solutions were available:

1. BTES technology paired with recharging solar collectors, a short-term heat exchanger thermal storage tank and a ground source heat pump connected to a system of eight fan coils distributed around the warehouse. as shown in Fig 1. BTES has the potential for commercial viability on a smaller scale and is frequently used at the domestic level [1]. During the summer months (1st April to 30th 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. 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.

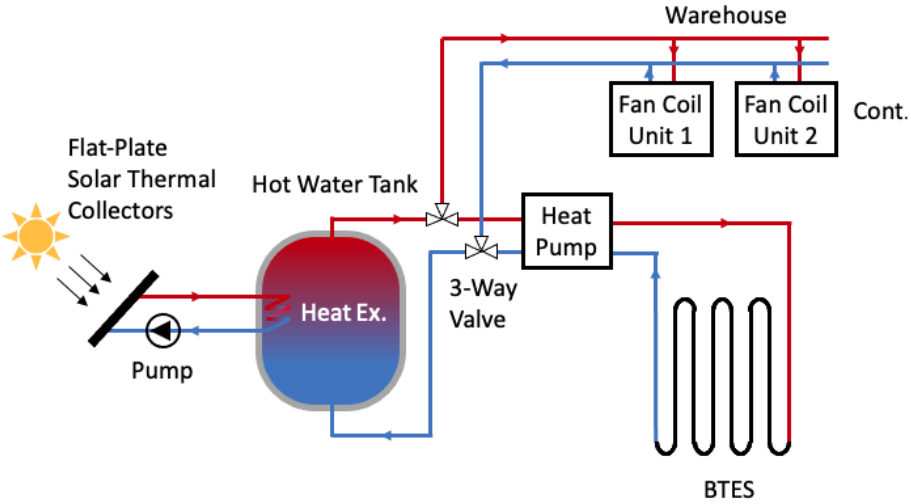


Figure 1 - Schematic diagram of the proposed BTES warehouse heating system during borehole charging. During winter, the solar collectors are disconnected, and the system runs in the opposite sense.

2. Replace the boilers with a reversible 400 kW air-to-water heat pump connected to eight fan coils to heat the space in the winter months, as in Fig. 2. The problem with this is the low ambient temperatures during winter reduce the CoP and lead to higher electricity costs. This system could also cool the warehouse in summer, but since cooling is not present in the current system, this has not been included in the calculations.

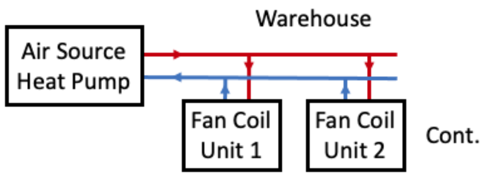


Figure 2 - Schematic diagram of the proposed ASHP warehouse heating system

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

Fig 3. shows only the assumed values, but in some cases a range of uncertainty was provided. Required energy delivered and running time will match those of the conventional diesel system (Table 1) [3], and a 10 % discount rate is typical for the industrial sector [4]. 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 components in these systems.

Prices and Tariffs: Displayed values were true as of 5/4/2021. RHI Tariffs increase in line with the Consumer Price Index but have been treated as fixed for this analysis. Propylene glycol prices are assumed to be fixed, as a future change in their 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. The assumed value is their value as of the 5/4/2021, and maximum and minimum values were estimated based on 10-year historical data.

Diesel: Unit price, rated efficiency and current and voltage figures are from the Powrmatic CPx 90kW diesel boiler [10] datasheet [11]. Five such units are used in the current system. Diesel energy density varies, but 38 MJ/L is common for industrial diesel [36].

Fan Coils: Unit cost and power consumption are for the Reventon 50kW Fan Coil [12]. Eight such units are required in each replacement system.

ASHP System: No price was given for the 480 kW ASHP, but a price of £150k was assumed from multiplying the cost of smaller units [15], with range of uncertainty of £100k to £200k. Heating capacity and CoP were obtained from the datasheet [16]. The ASHP must be serviced annually to comply with RHI requirements [18]. It has been assumed that a flat-rate annual service will be provided by the manufacturer, including parts and heat transfer fluid replacement. A CoP of 3.4 is quoted for an outdoor air temperature of 7°C and a hot water temperature of 35°C [16]. A CoP range was provided to account for uncertainties in air temperature.

BTES System: The heat transfer fluid should contain 50% propylene glycol to prevent freezing which can damage the solar collectors [45]. The GSHP unit price, rated power and CoP are for a Dimplex GSHP with output of 108.5 kW [20]. Four units will be cascaded, for a total rated output of 434 kW. Unlike the boreholes, the solar collectors are not a closed 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 AR Solar Collector datasheet [24]. An uncertainty range has been provided for the heat removal factor, the materials and installation cost per m^2 and the inlet and outlet fluid temperatures. Collector overall heat loss coefficient also varies but has been taken as a fixed value as it has little effect on the final cost. A pipe, valve, and tank heat transfer efficiency of 80% has been included to account for additional system thermal losses. Boreholes have an expected service life of 50 years, much longer than the project scope. At a low temperature and pressure, sandstone is more

Discount rate	0.10	[4]
Project scope (Years)	20	
Prices and Tariffs		
RHI Tariff - Solar thermal (£/kWh)	0.1112	[5]
RHI Tarff - ASHP (£/kWh)	0.0278	[5]
Electricity cost as of 05/04/21(£/kWh)	0.16	[6]
UK diesel price as of 05/04/21 (£/L)	1.291	[7]
Assumed propylene glycol price (£/L)	5	[8]
Diesel (Current solution)		
Expected diesel boiler service life (years)	20	[9]
Assumed 90kW diesel boiler unit cost (£)	3,750	[10]
Diesel boiler rated efficiency (%)	92%	[11]
Assumed energy density of diesel (MJ/L)	38	[36]
Current drawn by fan (A)	12	[11]
Voltage supply (V)	230	[11]
Fan coils (Used in both proposed solutions)		
3-stage fan coil 50 kW unit cost (£)	500	[12]
Fan coil expected service life (years)	20	[13]
Single unit power consumption (kW)	0.19	[14]
ASHP System		
AQUACIAT 480kW 2000 c ASHP unit cost (£)	150,000	[15]
Heating Capacity (kW)	480	[16]
Assumed ASHP lifespan (Years)	20	[17]
Assumed installation cost (£)	5,000	
Annual service inc. replacements (£)	2000	
Assumed ASHP CoP	3.4	[16]
BTES System		
% Propylene glycol in heat transfer fluid	50	[45]
Ground Source Heat Pump		
Expected heat pump service life (years)	20	[19]
108.5kW GSHP single unit cost (£)	42000	[20]
Rated power of total installed capacity (kW)	434	[20]
Assumed heat pump CoP	4.5	[20]
Flat-Plate Solar Collectors		
Expected heat transfer fluid service life (years)	5	[21]
Assumed solar collector service life (years)	25	[22]
Assumed efficiency of pipe, valves and tank	0.8	
Collector Heat Removal Factor (Fr)	0.6	[23]
Transmission Coefficient of Glazing (τ)	0.96	[24]
Absorbtion coefficient of plate (α)	0.95	[24]
Fluid volume/m^2 solar collector (L/m^2)	0.28	[24]
Collector overall heat loss coefficient (W/m^2)	1.2	[25]
Annual collector yield (kWh/m^2)	499	[24]
Assumed inlet fluid temperature, Ti (°C)	25	[25]
Assumed outlet fluid temperature, To (°C)	55	[25]
Assumed cost per m^2 solar collector (£)	400	[26]
Borehole and Ground Properties		
Expected borehole service life (years)	50	[46]
Assumed borehole thermal efficiency (η_o)	0.33	[1]
Installation cost per borehole (£)	5000	
Vol. heat capacity of sandstone (MJ/m^3K)	1.84	[28]
Thermal conductivity of sandstone (W/mK)	2.71	[29]
Borehole thermal resistance (K.m/W)	0.08	[30]
Heat Storage Tank		
Expected heat storage tank service life (years)	20	[32]
Assumed heat storage tank unit cost (£)	9000	[33]
Single unit volumetric capacity (m^3)	22.73	[33]
Vol. heat capacity of water (MJ/m^3K)	4.18	[34]

Figure 3 - Key assumptions on which the analysis is based. Only assumed values have been provided. Value ranges are provided in the spreadsheet.

porous and is expected to have a reduced heat capacity. A BTES efficiency of 33% has been assumed, which is typical in the first year of operation. This often rises with time, but usually stays below 50%. The largest available thermal storage tank was 5000 gallons (22.73m^3), and multiple tanks would be required to store the daily heat generated by the collectors. An average value of specific heat capacity of water was chosen based on the thermal operating range of the system (11°C to 55°C)

Techno-Economic Model

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

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

BTES System Technical Calculations

Required heat storage volume and number of boreholes: The cylindrical volume of earth needed for thermal energy storage was calculated using (1), where $Q_{tot}\,(MJ)$ is the total heat energy that must be supplied by the system, $c_{v,sandstone}$ is the volumetric heat capacity of sandstone and η_0 is the borehole thermal efficiency. Annual temperature change ΔT was taken to be 20°C. The cylinder radius was then calculated using (2). Taking borehole depth *L* as 100m gave a low surface area to volume ratio of 0.2. Assuming 5m spacing [40], it was determined that 12 boreholes would be needed (Fig. 4). This was multiplied by the cost per borehole, and the cost of propylene glycol in the boreholes was added to find the total cost.

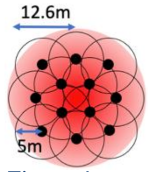


Figure 4 - Borehole spacing

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

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

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

Required heat storage tank capacity: The tank must be able to store the average daily heat generated by the solar collectors, $Q_{avg,daily}$ (Total heat generated during charging period (1 Apr – 30 Sept) divided by the 183 days in the period). 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 ΔT of 44°C. (11°C at the beginning of the day and heated to collector output temperature T_o = 55°C), just over 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: Initial cost is included in borehole and collector installation costs. Since the boreholes are a closed system, the fluid will not need replacing during the project scope. The volume of fluid in the V_{coil} is calculated with (6). $V_{per\,m^2}$ is the fluid volume per m^2 of collectors and *A* is the total collector area. The volume is multiplied by 1.05 to account for additional piping. Replacement cost C_{rep} is found with (7). β *is* the propylene glycol fraction and C_{pg} is the propylene glycol price per litre.

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

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

Fan coils annual cost of electricity: The known power of a single fan coil, P_{coil}, was multiplied by the number of coils in the system, *N*, the annual operating hours, T, and the price of electricity per kWh, C_{elec}, to find the annual electricity cost for the fan coils.

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

GSHP annual cost of electricity: This was calculated using (), where $Q_{charging}$ and $Q_{discharging}$ are the heat supplied to the borehole during charging, and to the warehouse during borehole discharging, respectively. C_{elec} is the cost of electricity per kWh.

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

ASHP System Technical Calculations

The two technical calculations for this system were the fan coil electricity costs, which has previously been calculated in (8), and the ASHP cost of electricity, which was calculated in a similar way as for the GSHP, but with the corresponding CoP and where Q_{tot} is the total heat delivered by the pump in a year (10).

$$C_{elec,ASHP} = \left(\frac{Q_{tot}}{CoP}\right) C_{elec} \quad (10)$$

Diesel Boiler Technical Calculations

Dividing the annual heat delivered (in MJ) by the diesel boilers by their assumed efficiency and the diesel energy density, U (MJ/L) gave the annual diesel consumption in litres. This was multiplied by

$$C_{tot,diesel} = \frac{Q_{tot}}{\eta_{boiler} \times U_{diesel}} \times C_{diesel} \quad (11)$$

$$C_{elec,fans} = P_{fan} \times N \times T \times C_{elec} \quad (12)$$

the diesel price per litre, C_{diesel}, to find the annual diesel cost (11). Using (12), the cost of electricity of the distribution fans was found. P_{fan} is the electrical power consumption of a single boiler, *N* is the number of boilers, *T is* the annual operational hours, and C_{elec} is the cost of electricity per kWh.

Economic Calculations

Simple payback period was calculated for each replacement system, where the denominator was calculated as: $Operational\ Savings = OPEX_{conv} + RHI\ Income - OPEX_{repl}$. The best-case scenario assumed $CAPEX_{conv}$ and $OPEX_{conv}$ to be at their maximum and $CAPEX_{repl}$ and $OPEX_{repl}$ to be at their minimum. The opposite was true in the worst-case scenario. For all three systems, a best-case, assumed, and worst-case Total Life-Cycle Cost (TLCC) was calculated based on minimum, assumed and maximum CAPEX and OPEX. LCOSE for the replacement systems compared to the original were calculated, factoring in total electricity and fuel consumption. In the best-case scenario the minimum investment was assumed for the maximum amount of discounted saved energy. In the worst-case scenario the opposite was true, and the assumed case used the most reasonable values. For the diesel and ASHP systems, capacity factor (CF) was calculated by dividing annual delivered heat by the total possible delivered heat if the system continuously ran at max capacity all year. For the BTES system, CF was found by dividing total heat delivered to the warehouse by the product of maximum solar yield (kWh/m^2) by the total solar collector area in m^2.

BTES with GSHP and Solar Collectors CAPEX	Best-Case	Assumed	Worst-Case	CAPEX (£/kW)
Borehole installation (£)	55,917	67,917	79,917	156.49
Thermal collectors (£)	441,924	700,878	1,072,283	1614.93
Heat pumps (£)	168,000	168,000	168,000	387.10
Short-term heat storage tank (£)	45,000	45,000	45,000	103.69
Total discounted decommissioning costs (£)	3270	3270	3270	7.5355371
Heat pump installation (£)	5,000	5,000	5,000	
Total Capital Cost (£)	719,111	990,066	1,373,470	**2,281.26**

BTES with GSHP and Solar Collectors OPEX	Best-Case	Assumed	Worst-Case	OPEX (£/kW)
Heat pump maintenance and callout (£/yr)	2,000	2,000	2,000	4.61
Cost of electricity for GSHP and fan coils (£/yr)	19,130	24,281	42,661	55.95
Heat-transfer fluid replacement (£/yr)	617	617	617	1.42
Storage tank maintenance and callout (£/yr)	200	200	200	0.46
Solar collectors maintenance and callout (£/yr)	2,000	2,000	2,000	
Total operating expenses (£/yr)	23,947	29,098	47,478	**67.05**

ASHP CAPEX	Best-Case	Assumed	Worst-Case	CAPEX (£/kW)
480kW ASHP unit cost (£)	100,000	150,000	200000	312.50
Installation cost (£)	5,000	5,000	5,000	10.42
Cost for all fan coil units (£)	4,000	4,000	4,000	8.33
Discounted ASHP decommissioning cost (£)	743	743	743	1.55
Total Capital Cost (£)	109,743	**159,743**	209,743	**332.80**

ASHP OPEX	Best-Case	Assumed	Worst-Case	OPEX (£/kW)
ASHP annual service (£/yr)	2,000	2,000	2,000	5.00
Cost of electricity for ASHP and fan coils (£/yr)	6,040	8,103	14,328	20.26
Total operating expenses (£/year)	8,040	10,103	16,328	**25.26**

Diesel Boilers CAPEX		Assumed		CAPEX (£/kW)
Assumed 80kW diesel boiler unit cost (£)		3,750		9.38
Number of units		5		
Total cost of five diesel boilers (£)		18,750		46.88
Assumed installation cost (£)		5,000		12.50
Total capital cost (£)		23,750		**59.375**

Diesel Boilers OPEX	Best-Case	Assumed	Worst-Case	OPEX (£/kW)
Total annual fuel cost (£/yr)	15,755	22,600	26,259	47.08
Maintenance (pipes, breakdown etc.) (£/yr)	500	500	500	1.04
Cost of electricity (distribution fans) (£/yr)	821	938	1,466	1.95
Total operating expenses (£/yr)	17,076	24,038	28,224	549.04

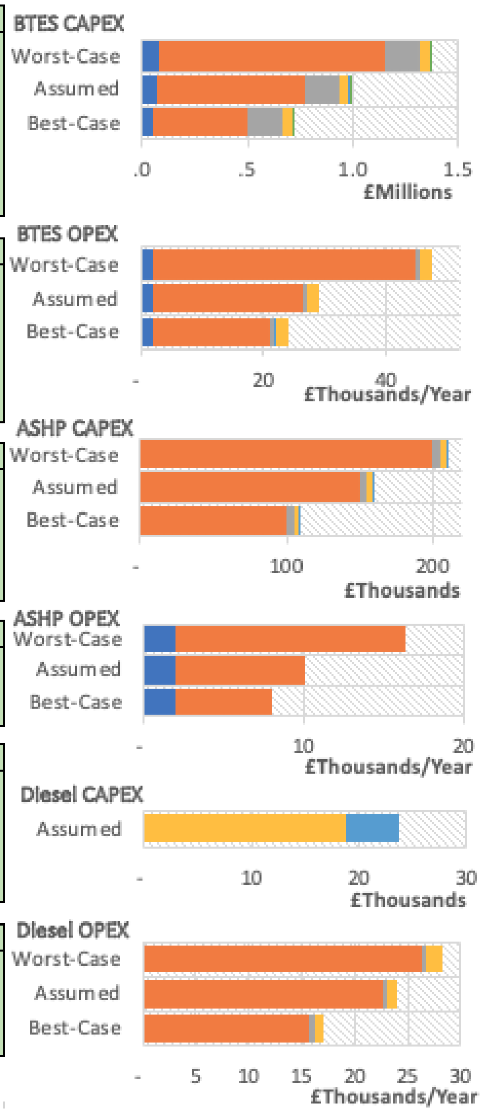
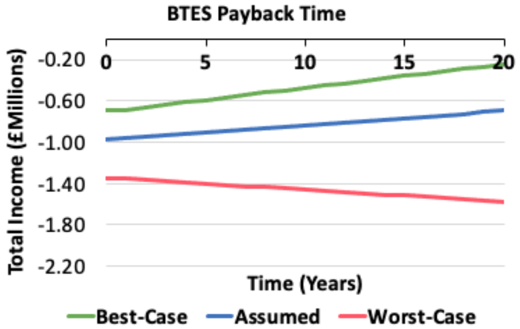
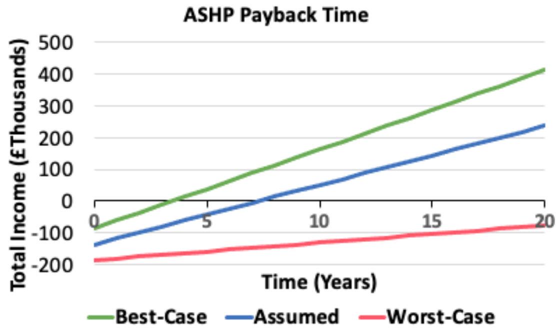


Figure 5 - OPEX and CAPEX for the two replacement systems and the conventional diesel system, separated by component. Best-case, assumed and worst-case scenarios are displayed. The diesel CAPEX is small and contains little capacity for variation, so no range has been provided.

	BTES System			ASHP System			Diesel Boilers (Conventional)		
	Best-Case (min costs, max savings)	Assumed	Worst-Case (max costs, min savings)	Best-Case (min costs, max savings)	Assumed	Worst-Case (max costs, min savings)	Best-Case	Assumed	Worst-Case
Total capital cost (£)	719,111	990,066	1,373,470	109,743	159,743	209,743	23,750	23,750	23,750
Total operational cost (£/yr)	23,947	29,098	47,478	8,040	10,103	16,328	17,076	24,038	28,224
RHI Earnings (£/year)	18,904	18,904	18,904	4,726	4,726	4,726			
Operational savings (£/yr)	23,181	13,844	(11,498)	24,910	18,661	5,474			
LCOSE (£/kWh)	2.13	4.20	14.02	0.13	0.19	0.30			
Capacity factor (%)	23.1%	19.4%	15.9%	4.0%	4.0%	4.0%	4.5%	4.5%	4.5%
Simple payback period (years)	-	-	-	3.45	7.29	-			
Construction time (years)	0.5	0.5	0.5	N/A	N/A	N/A			

Figure 6 - Total CAPEX and OPEX of each system, followed by RHI earnings, LCOSEof replacement systems compared to the conventional, capacity factor and simple payback period. Best-case, assumed and worst-case scenarios are shown. ASHP has negligible construction time so has





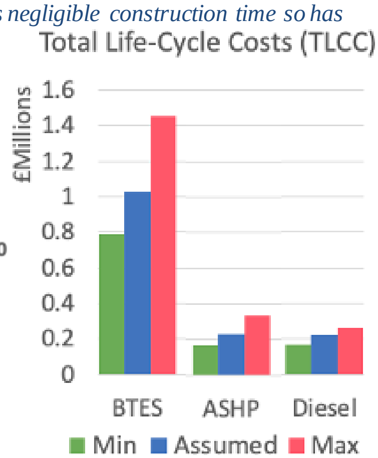


Figure 7 - The range of potential simple payback periods (SPP) for each replacement system. The missed savings and RHI payments during the 6-month BTES construction period were included in this calculation.

Results

Analysis and Discussion

The BTES system is unlikely to return a profit on the original investment due to high capital costs, the requirement for the heat pump to run during summer to recharge the boreholes, as well as the low thermal efficiency of the boreholes requiring high solar collector capacity. Fig. 7 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 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 is less affected by cold weather than the ASHP system, whose efficiency drops in cold climates. This means that the BTES system should become more viable in more northern climates. As well as the large lifetime costs, 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). This means the BTES system has a very high LCOSE, seen in Fig. 6. 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 for most decarbonisation projects [41].

There are some limitations of the BTES system. It can be hard to get drilling rigs to site, as they are quite scarce, and an upswing in the construction sector would make it almost impossible to get one to a small project site such as this. Due to the complexity of the system and its many components, a construction period of up to six months is envisaged, during which the diesel system would continue to operate. However, RHI tariffs are only paid once a system is operational, reducing the total savings generated by the BTES system within the project scope. Since Stanley is a former mining region, 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 boreholes [43]. This system would also be unable to cool the warehouse during summer, as the GSHP would be occupied with borehole recharging. Also, the complexity of the system increases the likelihood of a component failure, which could lead to downtime and maintenance costs.

The analysis revealed the ASHP system to be the more feasible option. The OPEX and CAPEX breakdown in Fig. 5 showed that variations in the ASHP capital cost, the price of electricity and the price of diesel would have the biggest impact on the feasibility of this this system. Its simplicity means that capital expenditure is much lower than for BTES. The conventional system could be replaced in days or weeks, and the construction period would have a negligible effect on returns. In the assumed case, at the current diesel and electricity prices, this system would break even just over seven years after installation and save more than £250,000 over the project scope (Fig. 7). In the best-case scenario the project could break even in around 3.5 years. In the worst-case scenario, a payback was not seen within the project scope, but this assumes an unusually low CoP of 3, and high per kWh electricity costs, resulting in a total cost of electricity almost double that of the assumed case.

The ASHP system had a much more attractive LCOSE, ranging from £0.13 in the best-case scenario, to £0.3 in the worst-case, with an assumed cost of £0.19/kWh, when applying a 10% discount rate. This partly because the ASHP has a significantly reduced lifetime discounted energy consumption compared to the conventional system, (0.37-0.49 GW for ASHP vs. 1.58 GW for diesel), meaning the change would be both economically and environmentally beneficial. One limitation of this system is its reliance on a single machine to provide heat in winter. This means in the case of a breakdown there would be no heat in the whole warehouse. In reality, there would have to be backup fuel-burning or conventional electric heaters, increasing the CAPEX. This could be mitigated using multiple smaller ASHPs in place of one. ASHPs also usually have a lower CoP than GSHPs, but in this case the overall energy consumption is lower as it is only active during the winter months, whereas the GSHP must also recharge the boreholes during summer. The Diesel and ASHP systems only run during the colder months and require a high output capacity to quickly and effectively heat a large, poorly insulated space. These systems could theoretically run 24 hours a day all year round, meaning their maximum annual heat output is large, and their capacity factors are low. However, their fuel and electricity costs are zero when not in use. Although the BTES system makes the most effective use of its available capacity, the CAPEX and OPEX per kWh of installed capacity is significantly greater than in the other two systems, making it less financially viable. The variation in BTES CF is due to uncertainties in required solar collector area.

Figure 8 - Total discounted life-cycle costs for each system, assuming a 10% discount rate

The best-case and worst-case scenarios are based on fluctuations in prices and capital expenditure figures that are unlikely to occur, especially not all at the same time. The likelihood that the 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 those of similar sized projects. However, it was sometimes uncertain what costs were included in these price estimations. There was also some uncertainty when estimating maintenance costs for each system. ASHP and GSHP installation and maintenance costs were assumed to be the same to reduce the impact on results, and 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 decommissioning costs were discounted and included in CAPEX. All components are assumed to be decommissioned at the end of the project scope, except the boreholes which can continue to be used in the future. It should be noted that the heat pumps and diesel boilers used had a capacity greater than the 400 kW required, slightly raising the CAPEX of each system. This is because it is difficult to find units with exactly correct outputs.

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