University of Oxford

Department of Engineering Science

B3 Group Design Project

Smart Local Heating Solution for Culham Science Park

Ben Robinson, Xiaoqi Chen, Dylan Affum, Emily Navidi

Trinity Term 2022

Contents

1 Introduction

Tackling climate change is a global initiative that has remained prevalent for many years. With the issues surrounding global warming continuing to grow, new strategies and incentives are introduced year upon year with the common goal in mind: to reduce the emission of greenhouse gases. Hoping to avoid what is described as "catastrophic climate change", the UK as part of the Paris Agreement, a legally binding international treaty on climate change, aims to limit global warming to 1.5°C above pre-industrial levels by achieving net-zero greenhouse gas emissions by 2050 [1][2].

Carbon dioxide (CO_2) in 2020 contributed to 79% of the UK's net territorial greenhouse gas emissions, estimated at an overwhelming 405.5 million tonnes carbon dioxide equivalent ($MtCO_{2equivalent}$) [3]. Now although generally falling, 2021 did experience a 4.7% increase in CO_2 when compared to 2020, in which one can observe the plausible link between this increase and the easing of Covid-19 lockdown restrictions where both non-domestic and public sector buildings began to open up their spaces once again [4]. With more than half of all emissions in the public sector coming from heating in the form of space and water heating, it becomes apparent that the decarbonisation of their heating is a necessary step in the right direction for a greener and more sustainable future. The emergence of Smart Local Energy Systems offers a solution that not only delivers "energy outcomes that are aligned with the specific resources of individual localities," but also contributes as "a key part of the fundamental change needed to get to net-zero" [5]. As a replacement for the "inefficient and unadaptable" traditional centralised energy systems which emit too much carbon dioxide, well integrated Smart Local Energy Systems have "the potential to bring cleaner, cheaper, more efficient energy to [local] communities," such as within Oxfordshire, while maintaining the balance between the generation and supply of renewable energy and the ever-changing demands of the whole community [6].

1.1 Specifications

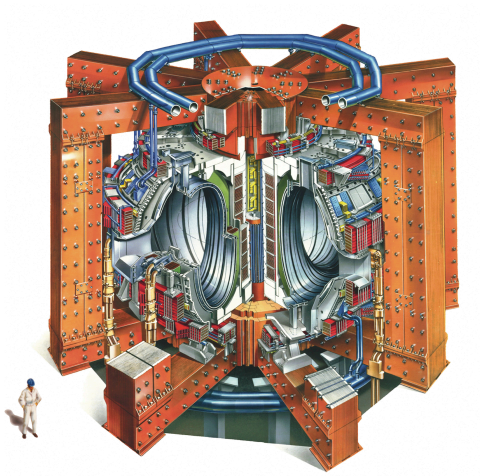
Considering the project brief, a detailed specification for our project was formed, as can be seen below [7]. It was decided that our solution must:

1. Provide heating and cooling to an iconic building such that it maintains sufficient internal temperatures for the particular uses of the building

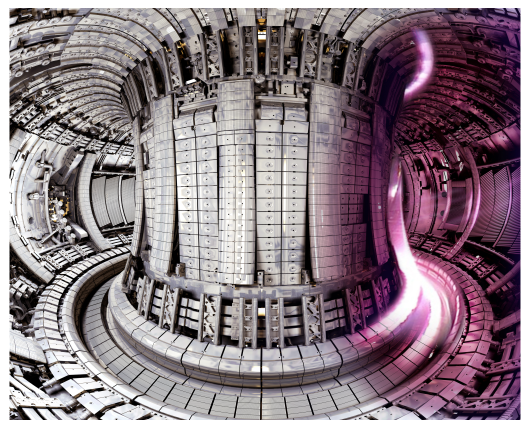
2. Replace existing carbon heavy energy sources with completely renewable energy sources

2.1.2 The Joint European Torus

Described as the "the focal point of the European fusion research programme" [12], the Joint European Torus, commonly abbreviated as JET and seen as both a sketch and vessel section image below in Figure 7 is "the largest and most successful fusion experiment in the world", having remained at the forefront of nuclear fusion experiments since beginning operations in 1983 [20]. It is for this exact reason that JET is so iconic, thus reinforcing why J1 has been selected as the iconic Oxfordshire building for our smart heating system. Within the the ring shaped vacuum chamber of the tokamak device called a torus, seen in Figure 7b, gaseous fuel is heated until plasma and then contained using powerful external magnetic fields. Hydrogen, deuterium and tritium are commonly used in the case of JET, which measuring in at 12 meters tall and 15 meters in diameter is the most powerful tokamak experiment currently operating [21].



(a) A 1980's drawing of the JET Machine [22]



(b) A section of plasma (pink), superimposed onto an internal vessel view of JET's ITER-like wall [22]

Figure 7: The Joint European Torus

Plasma, as seen in pink in Figure 7b is superheated matter which reaches temperatures greater than that of the sun's core, at hundreds of millions of Kelvins [23][24]. Reaching such temperatures requires a substantial amount of heating which works in conjunction with the previously mentioned powerful magnetic fields used to ensure heat is kept in the plasma. Now the JET fusion research facilities may appear to be inefficient to an outsider looking in, however it is argued that "they are efficient in their task, which is achieving the extreme conditions required to initiate fusion and [produce] plasmas on which to perform research" [24]. Although true, Section 6 will explore the waste energy within JET and look into its magnetic confinement system in particular - the largest consumer of energy and power on site.

3 System Overview

Following from the functional block diagram introduced in Figure 3 and in thoroughly investigating our demand, the problem of finding an exact means of providing heating to J1 can be tackled; this in conjunction with the utilisation of the available assets within J1 and the Culham Science Park. Focusing on the flow of heat, Figure 17 below introduces the main body of our proposed energy system for the heating and cooling of our building, J1, and its constituent elements and components.

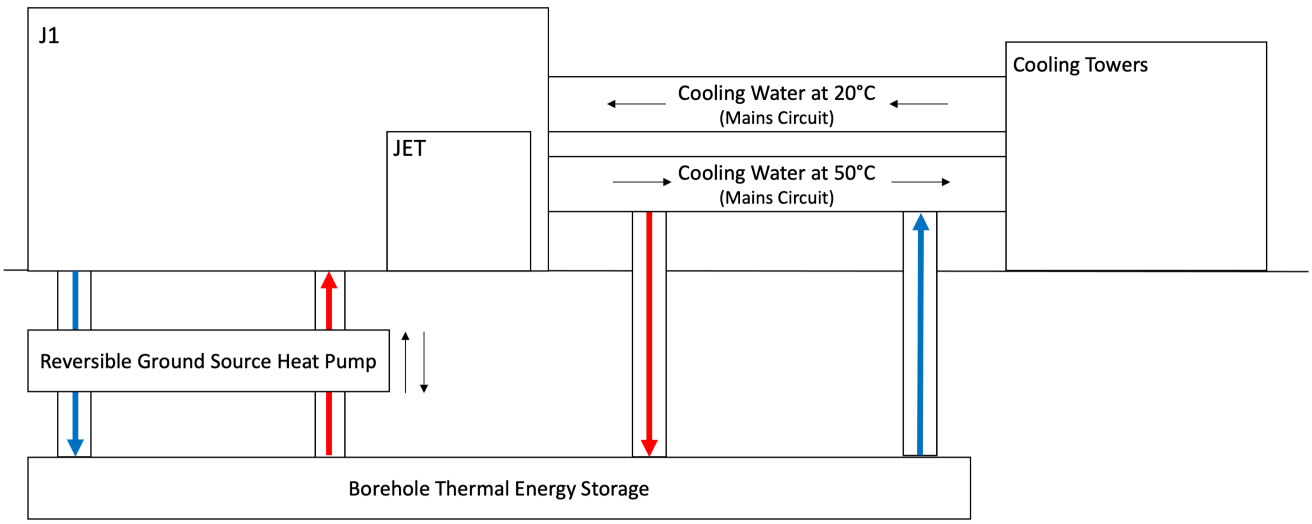


Figure 17: Simplified schematics of the heating system for J1, including the flow and directions of heat

The illustration above shows an annotated overview of our smart energy system, in which individual components will be further introduced in their respective sections to follow. The components shown interact together in order to achieve the required heating and cooling of J1, meeting our demand as previously investigated in Section 2.2. Here, the red arrows depict the provision of heat through hot water to a particular part of our system, notably to both J1 and the borehole storage, whereas the blue arrows depict the returning flow, now at cooler temperatures as the heat is used up accordingly.

When providing heating, the ground source heat pump (GSHP) operates under its usual working conditions and extract heat from the borehole thermal energy storage/system (BTES). Heat from our BTES is transferred via the GSHP to J1 through the form of hot water, in which the contained heat is subsequently distributed by the building radiators. The water now returns as a slightly cooler stream from J1, to be reheated again. Taking place occasionally throughout the year and along side the provision of heat, a supply of hot water leaves the operating hall and then J1 to be cooled by the on site cooling towers, after being heated as a result of the operation of JET. This supply is to be redirected through our BTES before

6 Waste Heat Utilisation

This section will explore the implementation and benefit of the recovery and subsequent utilisation of heat from the mains circuit water, this as it passes from J1 through to the cooling towers.

6.1 Exploration of Waste Thermal Energy

By sustaining plasma at temperatures in excess of the baseline 100 million Kelvin needed for the deuterium/tritium reaction, it is understandable why the powerful magnetic fields produced by the large coils within JET are a huge consumer of energy and power. Because of the resistance of the copper coils, significant heating is caused as large currents are passed through them. As a consequence, the coils need to be continually water-cooled to prevent the overheating of the facility, with energy dissipation occurring via the 'special' cooling towers explored below in Section 6.1.1 [24].

From the cooling system in place for the heating of coils in JET, it can be deduced that there is heat and subsequently thermal energy within the fusion facilities with potential to be harnessed if accessible. Here, the concept of accessibility is a vital one; an alternative proposal could've been to try to utilise the heat losses associated with the plasma heating itself however such losses in energy within the confined environment are neither feasible or recoverable. Being strict to this notion, it becomes apparent that the water in the main circuit (after interacting and being heated by the deionised water and Galden HT55 used directly to cool JET coils) is an appropriate medium to extract heat which otherwise is "dissipated to [the] atmosphere" via the same previously mentioned cooling towers which also are explored below [24].

6.1.1 Cooling Towers

Despite considered small when compared to those previously found at the Didcot Power Plant nearby, the JET cooling towers photographed and seen below in Figure 42 are far from it and are in fact massive with equally large connector pipes. Located close to the J1 building itself, and partnered with five large 200 kW pumps (which drive the circulation of the mains circuit), they provide cooling to 4 x 1000 m^3 of water per hour, from 50°C to approximately 20°C [24]. This corresponds to a significant capacity and total heat dissipation of 140 MW (megawatts) from using

$$\dot{Q} = \dot{m}C_p\Delta T, \tag{25}$$

of the multi-criteria analysis in Table 10 demonstrate why a vertical heat exchanger, specifically of the double u-tube borehole configuration is preferred for use in our particular system, and why it is to be considered for implementation here.

6.3 Implementation

6.3.1 Heat Exchanger Design

Having decided on the use of our boreholes in the double u-tube configuration for not only heat storage but also for heat recovery and utilisation, as seen in Figure 44, its implementation and incorporation into our overall system can be further investigated, now with the focus on the heat recovery itself.

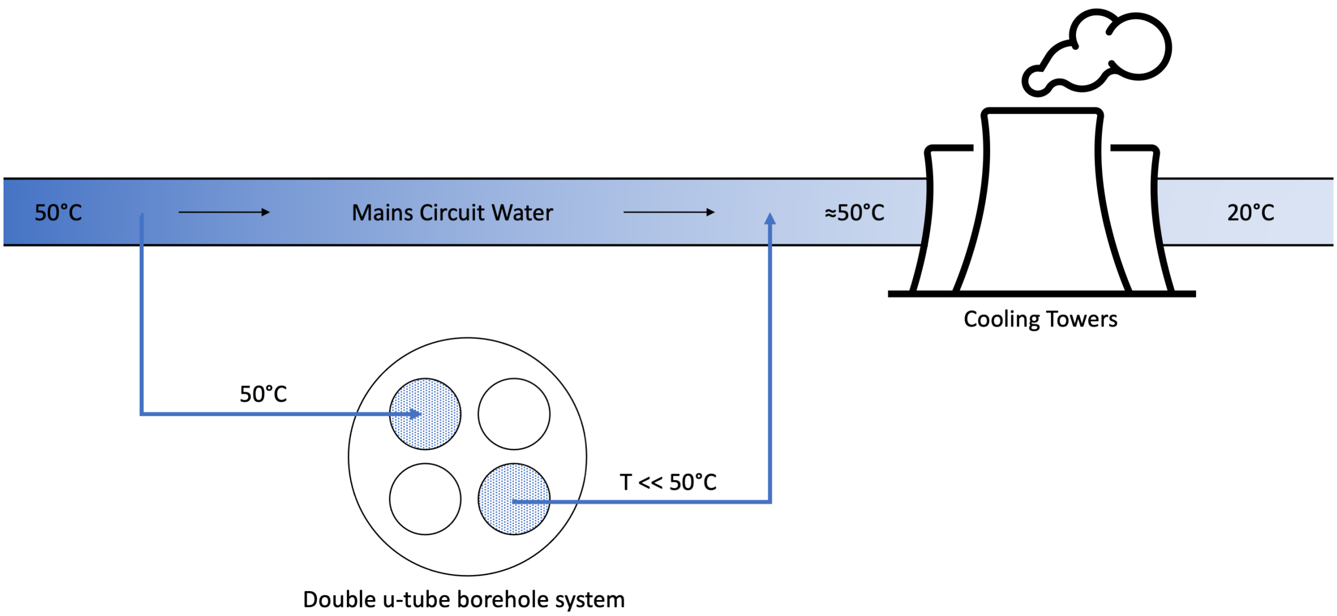


Figure 44: Schematic of the redirection of a proportion of mains circuit water through the double u-tube borehole system for heat recovery, prior to its return to bulk flow for cooling in the cooling towers

Simplified here to a single borehole, the process illustrated in Figure 44 above demonstrates the heat utilisation procedure intended to supplement and replenish the borehole system with heat, as is used up to provide heating to J1 through our ground source heat pump; this will occur simultaneously within each of the 21 boreholes which act in parallel. Each borehole will act as its own vertical heat exchanger, each supplied with a proportion of mains circuit water, entering at 50°C; the proportion of redirected flow will pass continuously through to supply heat and raise the temperature of the borehole before returning to bulk flow at a slightly reduced temperature. Richmann's law, as later populated in Equation 29 is considered here and imposed to observe that provided only a small proportion of the mains circuit flow is redirected through the 21 boreholes (relative to the entire flow) and rejoins bulk flow further along at a lower temperature, the cooling tower entrance temperature remains greater than 20°C, which is imperative as discussed earlier for the later stage heat exchange with the deionised water and Galden HT55.

Now in delving deeper into the implementation, the focus going forward will turn to addressing exactly how the double u-tube borehole design will operate to extract heat and:

- When will the redirection of take mains circuit water take place, and when can it not?
- What proportion of the mains circuit water will be redirected through each borehole?
- How much heat can and will we recover and utilise from the mains circuit supply?

These questions will be answered as this section continues to progress.

6.3.2 Assumptions, Limitations and General Considerations

Though a recirculating supply, the mains circuit water is not flowing all year round due to the experimental nature of the JET machine; for this reason, we cannot whatsoever extract and deposit heat into the ground on days that JET is not in operation. When JET is however operational, the continuous cooling system in place is too and so are the cooling towers to cool the mains circuit water. Understanding the operational times of the cooling towers would lead to understanding the flow of the mains circuit however such information was not able to be uncovered; consequently, the link between JET operation and the running of the mains circuit flow through the cooling tower is investigated further.

With the “overheating of the JET coils [being] the main limiting factor for the duration of the JET discharges, [...] the cooling system has been designed so that after each discharge the facility can be cooled down in 15 minutes”, enabling all data acquired from the JET diagnostic systems to be downloaded and saved [24]. Considering the importance of saving the diagnostic data as well as preventing the sharp increase in coil temperature, it is apparent that the risk of overheating will be closely monitored and controlled with the cooling of the coils not only during discharge, but continuously during JET operation to ensure “all of the resistive loss is removed by the cooling system” [120].

To understand the frequency of JET operation throughout the year, the 2019 C38 experimental campaign in deuterium which ran from the 17th June until the the 20th December 2019 is considered. Figure 45 below shows in extract the first week of the programme timeline, in which after there were over 180 working sessions where 46 experiment were executed across 48 weeks on the JET device [121].

6.3.3 Environmental Considerations, Social Equity & Economic Prosperity

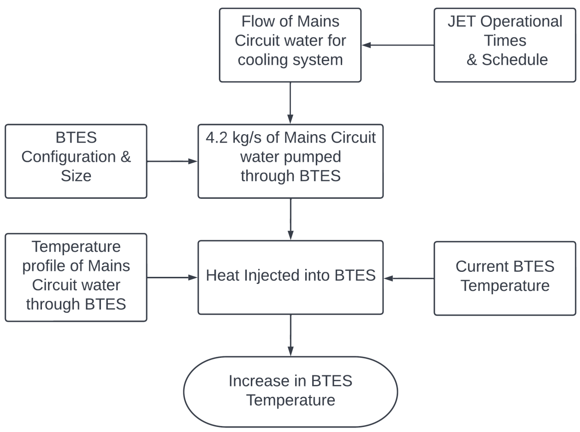
The advantage of our system is that otherwise wasted heat is used to replenish heat back into the ground/BTES to replace what we are extracting and as previously mentioned, this reduces the strain and work done by the GSHP unit. The subsequent economic benefit arising from this is by lowering our GSHP's demand on electrical supply, we are lowering our expenses towards our form of electricity generation, as to be discussed in Section 7.3. It is however expected that the ground in close proximity to our BTES will experience an increase in temperature from ordinary levels to facilitate this. With emphasis on the environmental considerations towards the amount of heat from the mains circuit water transferred to the BTES, a concern here would be of dumping too much heat into the ground such that it becomes a safety hazard - this must be addressed. To understand the regulations surrounding this and any possible restrictions on maximum ground temperature, both the Environmental Agency (EA) and the Health and Safety (HSE) websites and supporting documents were inspected. Neither emphasised any concerns or regulations regarding the increase in ground temperature in the case of boreholes, or at all, suggesting this rather to be something to consider depending on the exact case considered and location. As learnt from the case of Brent Spar, although this may not void any regulations, the EA would be involved during the early planning stage as a precaution and the system would warrant continuous environmental and safety assessment during the lifetime of the BTES on top of the initial assessment conducted in Section 5.4 to ensure that firstly, there are no expected detrimental environmental effects further on and secondly, that the raised ground temperature doesn't become a safety hazard for employees at Culham. It is also encouraged to involve stakeholders such as the UKAEA, but less obvious too the many Culham Science Centre employees in such decisions as to reinforce social equity and attain perspectives not wholly centred around the economic benefit but with consideration for social equity and environmental quality too. The land, although clear and operable, may have been of use to employees during their lunch break as an example and hence it is important to involve their perspectives towards the development.

6.3.4 Pump Sizing & Costs

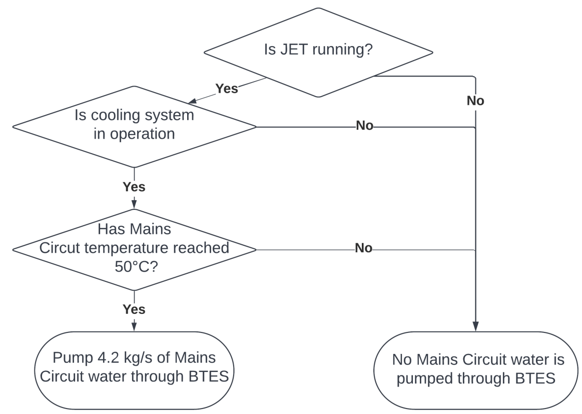
Complimentary to the two system water pumps discussed later in Section 7.2, the third and final pump which pumps the mains circuit water through the BTES, and then back to rejoin the bulk flow heading to the cooling towers will be explored and appropriately sized here. Taking into account the borehole depth and the maximum round trip from J1 to the BTES location and then back to the cooling towers,

6.4 Heat Recovery

Seen below in Figure 47 are the inputs into our control system, summarising as and when we are able to recover heat, and what determines the amount we can recover.



(a) Flow chart showing inputs determining the amount of heat injected into the BTES



(b) Control System Decisions

Figure 47: Flow charts showing the heat recovery process

As a smart system, the response of all live inputs as seen in Figure 47b will be fed into our control system and updated to determine when mains circuit water will be redirected and heat recovery will occur. With thought towards computational capacity and expense, inputs need only be fed into the control system and updated a handful of times a day to check for JET operation and the flow of the mains circuit water.

Figure 48 shows a schematic of a singular borehole, part of the 21 collective that form our BTES; for simplification, it will be taken as representative of our entire BTES system

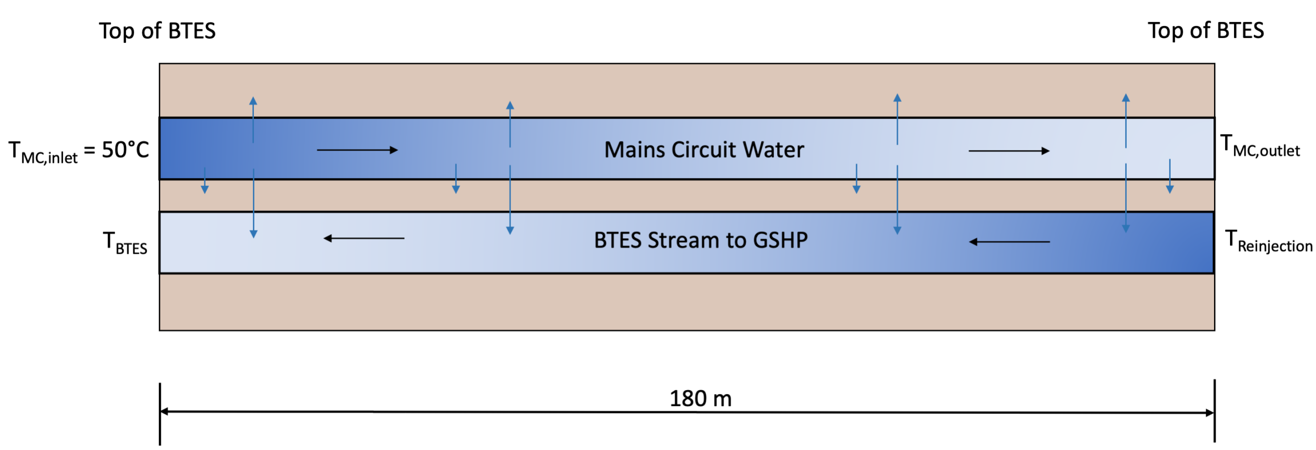
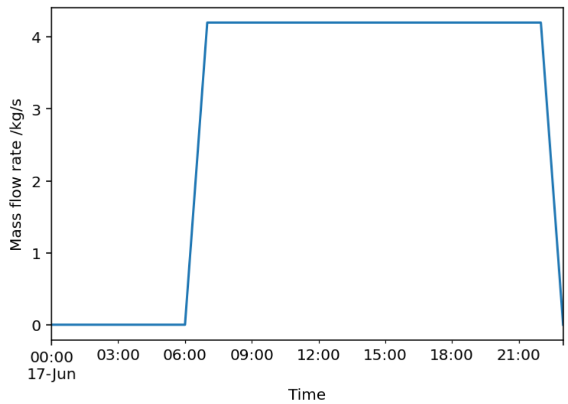
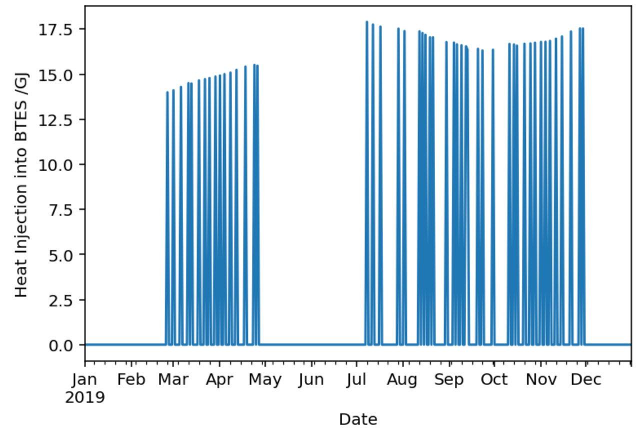


Figure 48: Schematic of the double u-tube pipes and the surrounding grout within a single borehole

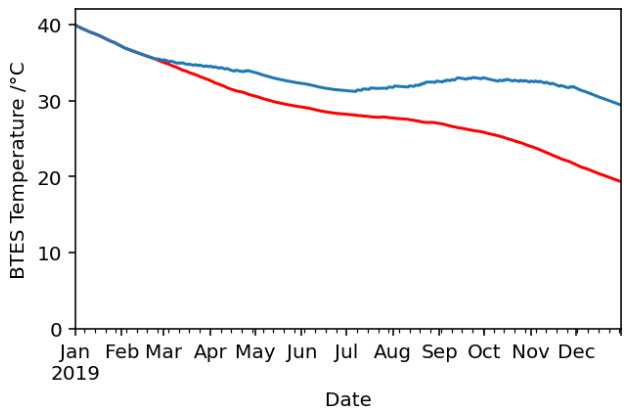


(a) Flow of redirected mains circuit through BTES during days of heat recovery

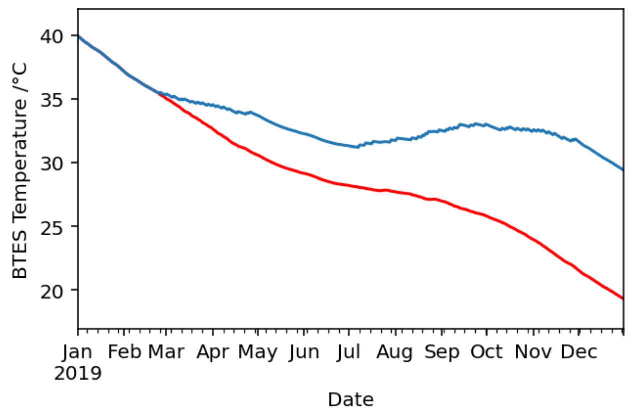


(b) Heat recovered from redirected mains circuit water, which is subsequently injected into BTES

Figure 50: Injected flow of mains circuit water into BTES and subsequent heat injection



(a) Comparison of T_{BTES} with (blue) and without (red) injection of heat from mains circuit water



(b) Granular comparison of T_{BTES} with (blue) and without (red) injection of heat from mains circuit water

Figure 51: Effect of heat injection on the BTES temperature during first year of operation

The increase and improvement to T_{BTES} during the first year of operation can clearly be observed, highlighting the success in raising the BTES temperature while slowing down the depletion of heat in the ground as is used up to heat J1. It can be seen to fall to near our expected steady state BTES temperature of around 30°C, as defined in Equation 16 of Section 4.2.3. Despite this, it too poses as a slight concern when considering the slight temperature decline at the start of the following year and the subsequent effect on our GSHP's COP however this will be analysed in Section 6.5.

6.4.1 Initial Charging of BTES

With the utilised heat aiding to supplement heat into the BTES, it is apparent that the BTES must undergo a period of initial thermal charging to enable it to reach a high enough temperature to then draw from, as

6.5.1 Replicability

Renewable methods of heat generation are implementable in most buildings, provided matched with the necessary improvements to insulation, however it is the utilisation of waste heat which makes our system unique to many others. Limited here by the frequency of JET operation, many places within Oxfordshire alone show promise for similar and possibly more regular heat recovery and utilisation.

Unipart Yutaka Systems (UYS) Oxfordshire, the BMW MINI Manufacturing plant and the John Radcliffe Hospital are among the non-domestic and industrial buildings within Oxfordshire registered with either cooling towers or condensers [131][132]. Although unlikely to be as large as those found on the Culham site, they are likely to be in operation far more frequently through the year allowing for, as previously mentioned, more regular heat utilisation (although the manner in which they do so may differ due to other constraints, such as land available nearby, and the particular method of heat generation favoured).

The regular but varied flow possible with the implementation of a system similar to ours at these locations would ensure a more stable annual BTES temperature, advantageous to a GSHP if to remain as the provision of heat. If such systems were to be replicated in these buildings, the potential for a heat network, forming “a distribution system of insulated pipes that takes heat from a central source and delivers it to a number of domestic or non-domestic buildings,” could arise in which heat is extracted from the ground as a common source, and later replenished with waste heat [133]. On a slightly smaller scale however, the Culham Science Park is home to a plethora of non-domestic buildings all of which could also benefit similarly from the improvements we have suggested for J1, with potential even for a smaller and more local heat network. The amount of mains circuit flow utilised is less than 1% of the entire flow; this suggests that there is still plenty of heat to be recovered and optimised. There too is still operable land on the site in which further boreholes could be placed, allowing these buildings to also be heated with heat extracted from site grounds, which can then be replenished as proposed here.

The incentive for such heat networks includes the benefit from programmes such as the government funded Heat Networks Investment Project (HNIP) which offers “£320 million of capital funding to gap fund heat network projects” [134]. This in itself, partnered with the aim for increasing low carbon heating is great motive for scaling up our system, aided with funding to support more boreholes and an even greater heat pump unit. Similar to the HNIP, the Green Heat Network Fund (GHNF) is a three-year grant offering £288 million of capital funding. Only having opened recently on the 14 March 2022, this scheme will run until 2025 providing even more incentive for the consideration of a local heat network [135].

10 Project Financing

10.1 Subsidies and Grants

The Non-Domestic Renewable Heat Incentive (NDRHI) for commercial, industrial and public buildings such as J1 is "a government environmental programme that provides financial incentives to increase the uptake of renewable heat by businesses, the public sector and non-profit organisations" [163]. With our system GSHP meeting the eligibility requirements detailed by Ofgem, this scheme offers "quarterly payments over 20 years based on the amount of heat generated," with the most up to date payment for a 150 kW GSHP such as ours set at 4.73 p/kWh for tier 1 payments and 1.41 p/kWh for tier 2 [164][163][165]. Although advertised as closed to new applicants, Ofgem have mentioned they "have started to assess a selection of applications that were submitted on or after 01 September 2021" allowing this scheme to still be considered for our system [166], with calculations summarised in Table 12 below.

Table 12: Payment from the NDRHI for our GSHP

	Upfront Cost (£)	NDRHI Tariff (p/kWh)	NDRHI Yearly Payment (£)	NDRHI Total Payment (£)	NPV after 20 years (£)
GSHP	-45,000	1.41 - 4.73	9,802	196,040	94,315

This takes into account that our demand is to be met in its entirety by our GSHP for the 'simple system' payment calculation [167]. With a discount rate of 3.5% as given by the UK's social time preference rate, the positive Net Present Value (NPV) for the GSHP highlights how we can benefit from this scheme [168].

The Public Sector Decarbonisation Scheme (PSDS) aims to provide funding to cover the capital costs for eligible low carbon heating technologies, such as our ground source heat pump. Introduced in late 2020, with phases 2 and 3 in 2021, this scheme will see future phases for available projects starting in the financial year 2023/24 onwards making it the perfect scheme to aid in covering the capital costs for our system. In looking at the recipients of the first phase PSDC, grant values ranging between £737,200 and £6,783,486 were allocated to research and innovation sites in the UK to "install insulation and replace ageing gas boilers" as well as "heat pumps and solar panels" [169][170]. With this in mind and in exploring the different cases approved and the sum and allocations of their grants, it can be expected to apply and be approved for up to a conservative £1-1.5 million which from our cost breakdown to be seen in the section to follow, could cover almost the entirety of the capital costs towards our system, with the remaining costs expected to be covered by the UKAEA as the parent body for the CCFE.