Northern Powergrid

LDR Tranche 1 - Transformer Heat Recovery

Transformer Heat Recovery Project Report

Issue | 04 October 2018

Job number 260324-00

Ove Arup & Partners Ltd
www.arup.com

ARUP

Contents

Executive Summary

The aim of this study is to investigate the potential for heat recovery from Northern Powergrid substations, to present a concept technical heat recovery solution and an outline cost-benefit assessment.

The proposed concept heat recovery solution integrates an oil-to-water heat exchanger and a brine-to-water heat pump alongside the existing transformer air cooling system, to enable heat recovery and upgrade of recovered heat to temperatures suitable for use in heating systems, without compromising the operation of the transformer.

The results of this study conclude that heat recovery from existing Northern Powergrid substations is technically achievable where local heat demands can be identified. However, the analysis concludes that to do so would not be commercially viable. Sensitivity analyses of the prevailing variables reveals that low temperature operation of the heat pump along with novel heating designs, such as delivery of heating water to demand side boiler return headers, could enhance profitability and scheme viability.

Further sensitivity analyses indicated that increases in heat sale tariff render the schemes increasingly economically viable; however, a heat purchase agreement with sufficiently high tariffs could result in a profitable heat recovery scheme, however ensuring the attractiveness of such a scheme would be difficult under current market conditions.

1 Introduction

Arup was commissioned by Northern Powergrid (NPg) to investigate the potential for heat recovery from major transformers at grid supply points and primary substations. This report describes the findings of our research and presents concept technical heat recovery solutions and outline cost-benefit assessments for identified suitable substations. This report follows preceding work on substation mapping and shortlisting which is provided as an appendix to this report.

Heat recovery may be implemented as a retrofit solution, or may be engineered into new substation design. Although this study focussed on NPg’s existing substations (and therefore retrofit solutions), it is recognised that engineering heat recovery into new substations can be beneficial, not only for the utilisation of waste heat, but because transformer size is reduced when OFWF cooling is used and this is particularly attractive where space is an important constraint. On the other hand, it should also be considered that new substations are likely to utilise lower-loss transformers and in the future, new materials and equipment designs may be available to take loss reduction even further.

2 Heat Recovery

2.1 Heat Recovery Principles

Energised transformers experience losses mainly in the form of heat. Recovery of this heat could contribute to space heating and domestic hot water requirements. Waste heat recovery from substations also presents opportunities from a commercial standpoint, enabling the asset owner to gain returns on an otherwise wasted resource through the sale of the recovered heat to consumers.

The substation losses consist of two primary constituents namely, no load losses, which are independent of load and are produced in the transformer core when energised, and load losses, which are dependent on transformer loading. Transformer loading is variable, and as such the load losses and therefore the extent of heat generated by the substation varies with time. Consequently, in substation heat recovery systems, there is potential for mismatch between supply and demand, resulting in benefits for incorporating thermal storage to balance the system.

Heat pumps can be used to upgrade the recovered low-grade heat to temperatures suitable for use in heating systems.

2.2 Technical Concept

Recent research suggests that the recoverability of heat from substations varies as a function of the employed transformer cooling mechanism. A report produced by Imperial College London and Sohn Associates[1] suggests that Oil Directed Water

[1] Management of Electricity Distribution Network Losses, Imperial College London, Sohn Associates, 2014

Forced (ODWF) transformers exhibit the highest potential for heat recovery, whereas Oil Natural Air Natural (ONAN) transformers exhibit the lowest potential.

NPg major substation transformers operate using an ONAN configuration. Most of these transformers have a built-in capability to run oil pumps and fans in an air cooling unit to operate as Oil Forced Air Forced (OFAF) transformers to enhance their ratings under certain fault conditions.[2] The concept level technical solution for heat recovery has therefore been developed for the ONAN transformer configuration as this operating mode will be used for the majority of the transformer's life. This is presented in Figure 1 below.

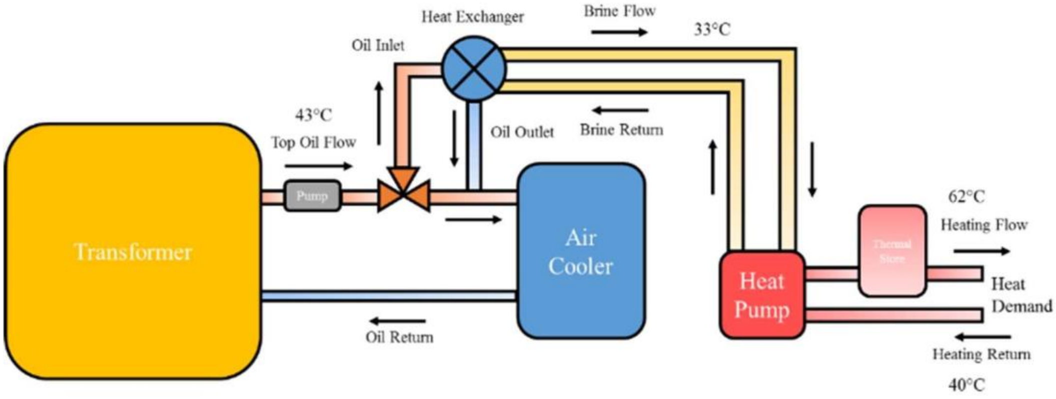


Figure 1: Schematic for heat recovery for major substation transformer converted to OFWF

The solution integrates a range of technologies alongside the transformer and its existing air cooling unit to enable the recovery of heat, namely; oil and water pumps (duty and standby), a three-way valve, an oil to water heat exchanger, a brine to water heat pump and a thermal store.

In the eventuality that the heat pump system requires maintenance, the position of the three-way valve may be changed to close off the line to the heat exchanger and direct the top oil flow directly into the air cooler, resulting in a configuration similar to that which is currently in operation at NPg substations. It is noteworthy that operation of the proposed technical concept solution changes the 'normal' operational configuration of the transformer from ONAN to OFWF.

The solution enables recovery of heat via the following mechanisms:

1. Energisation and loading of the transformer generates losses in the form of heat, which is transferred to the transformer top oil, raising its temperature.
2. The top oil is subsequently pumped through the three-way valve, which directs the top oil flow towards the oil-water heat exchanger.
3. A pump circulates the brine through the oil-water heat exchanger. Heat from the transformer top oil is then transferred to the brine circuit, raising

[2] More information on NPg transformer ratings is available from IMP/001/918 Code of Practice for Transformer Ratings

the temperature of the brine in circulation. In turn this reduces the temperature of the top oil.

4. The transformer top oil is subsequently fed into the air cooling unit, where its temperature may be reduced further by the cooling action of the ambient air, or by the action of cooling fans if the return oil temperature is above the desired threshold.
5. The heated brine flow exits the oil-water heat exchanger and is fed into the heat pump.
6. The heat pump utilises the heat from the brine circuit and uses electrically-driven vapour compression cycle to raise the temperature of the heating return water.
7. A water pump circulates the heated water to the heat demand via a thermal store. The thermal store enables temporary storage of generated heat to enhance system flexibility and reduce mismatch between heat supply and demand.

The practicality of implementing the heat recovery system was investigated during site visits to NPg substations, as discussed in the following section.

3 Site Visits

Site visits were carried out to identify site specific constraints/opportunities and to assess the practicality of implementing the concept heat recovery solution in NPg substations. The following section provides a high-level overview of the substation shortlisting process and presents the outcomes of the site visits. A detailed overview of the shortlisting process is listed in the Arup Overview of Substation Shortlisting Process Report in Appendix B.

3.1 Shortlisting Process

Integrated Risk Matrices (IRMs) and Geographical Information System (GIS) models were produced to inform a three-stage shortlisting process. Throughout the shortlisting process, a range of assessment criteria was evaluated to produce a shortlist of the ten most suitable substations for heat recovery. An overview of the assessment criteria used in each stage of the shortlisting process is presented in Table 1 below.

Shortlisting Stage	First Assessment Criterion	Second Assessment Criterion
Stage 1	The total annual transformer losses.	The sum of the gas consumption within a 1km radius of the substation.
Stage 2	The total annual transformer losses.	The proximity of the substation to heat networks.
Stage 3	The total annual transformer losses.	The proximity of substations to suitable heat loads.

Table 1: Overview of shortlisting assessment criteria

More detailed analyses of the annual and mean hourly transformer losses revealed that the quantity of heat generated by the assessed substations was insufficient to support commercially viable contributions to nearby heat networks. Equally, the number of substations within reasonable proximity of heat networks was limited. Consequently, the results of Stage 3 were used as the basis for identifying substations for site visits, assuming that recovered heat would be fed to local consumers, rather than heat networks and sold as part of heat purchase agreements (HPAs).

The loads near the shortlisted substations were assessed in greater detail in order to evaluate their suitability for receipt of heat and likelihood of engaging in HPAs. The Barrack Road and Scarborough Grid substations showed greater potential than others, and therefore these locations were selected for site visits. An overview of this final element of the shortlisting process is presented in Appendix C.

3.2 Barrack Road Substation

The Barrack Road 132/33 kV substation is situated in central Newcastle in the vicinity of St James' Park football stadium and a range of large accommodation buildings. The proximate heat load assessment identified the St James' Point accommodation building within 30 metres of the substation as a suitable load for receipt of recovered heat and engagement in a heat purchase agreement. There is opportunity to supply the accommodation building with heat, with relatively low observable constraints and trenching requirements.

Figure 2 below shows the St James' Point accommodation as the large grey and orange building to the right of the substation (highlighted in blue).

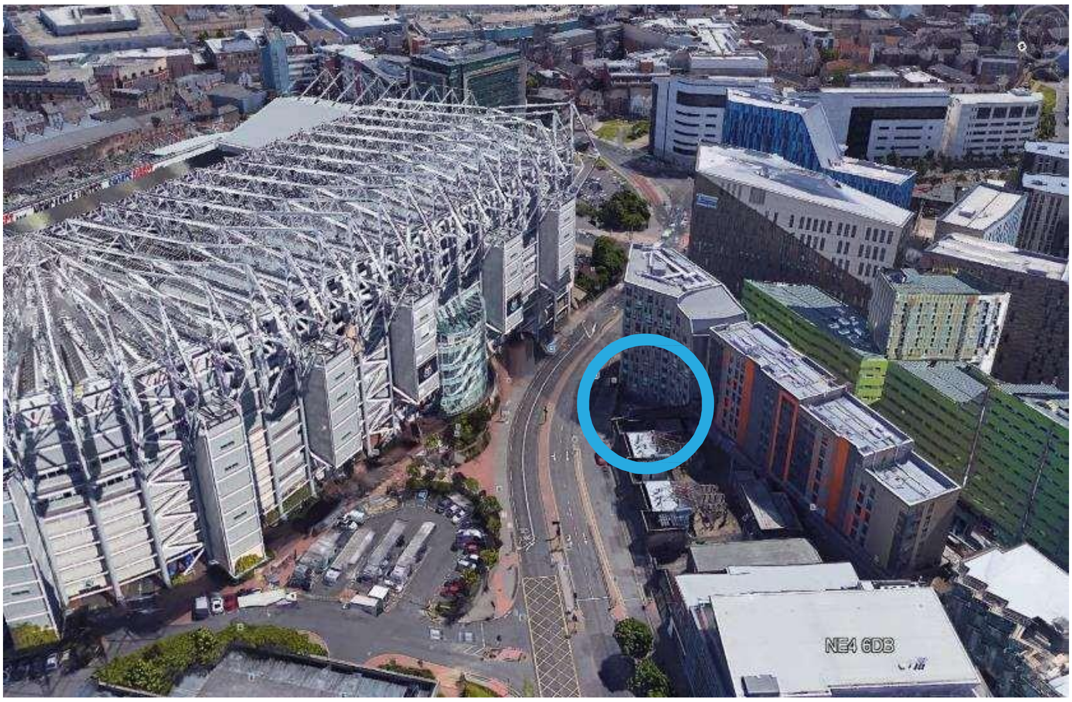


Figure 2: 3D Render of Barrack Road Site (image courtesy of Google Earth®)

One of the constraining features at the Barrack Road site is the presence of exposed live HV equipment, such as overhead lines and bushings, which require minimum clearances. The clearance requirements prevent the installation of electrical items, such as pumps/heat pumps within a set distance of the HV equipment and restrict the movement of personnel on site. As such, equipment must be installed at a minimum distance from the HV equipment and site access routes must be developed in order to install the heat recovery system. Figure 3 presents an overview of the Barrack Road substation site highlighting access routes and HV clearance zones.

Another key constraint at the Barrack Road is the availability of space for installation of heat recovery equipment. The two transformers located at the site are housed in buildings with an estimated maximum unobstructed area of approximately 0.7m by 0.7m. Consequently, major components of the heat recovery system, such as the duty and standby pumps, and the heat pump would have to be installed externally. An unused space towards the side of the site was identified during the site visit as a suitable position to install the equipment. This area is highlighted in as Zone 1 in Figure 3.

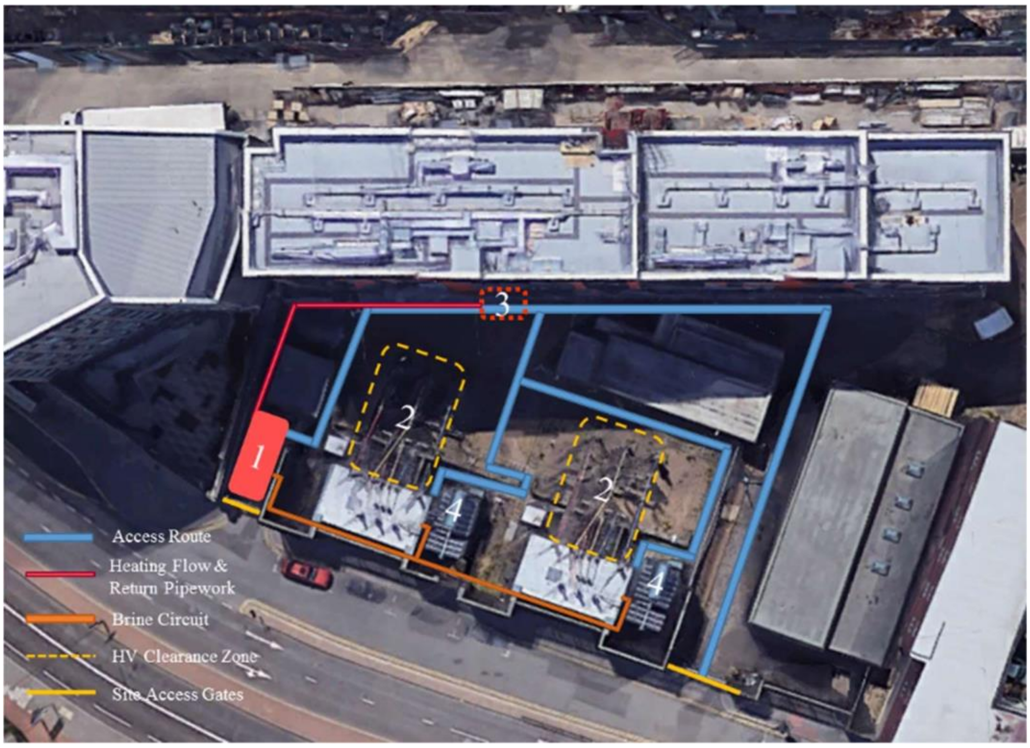


Figure 3: Barrack Road Heat Recovery System Site Plan (image courtesy of Google Earth®)

The figure highlights access routes, heating and return pipework routes, brine circuit pipework routes and HV clearance zones. The numbered items in the figure correspond to the following key locations at the site:

1. The location for the installation of the heat pump, brine circulation pumps (duty and standby), and the heating system circulation pumps (duty and standby).
2. High voltage clearance zones.
3. Estimated building plant room location and entry point of heating flow and return pipework into St James' Point accommodation building.
4. Existing air cooling units (adjacent to transformer housings).

The site access route has been developed in consideration of the practicalities of installation of the heat recovery system, aiming to satisfy minimum clearances from HV equipment, whilst also maintaining sufficient access to key areas of the site to enable installation. The location of the St James' Point plant room has been estimated and as such the heating flow and return pipework route is subject to change depending on the actual plant room location.

Discussion with an on-site engineer during the site visit led to the conclusion that it would be possible to integrate the proposed heat recovery solution into the existing transformer configuration, by replacing the top oil pipework with a pre-fabricated section of pipework containing a three-way valve. The spatial constraints at the site would prevent installation of the heat exchanger and associated pipework inside the transformer building, therefore the pre-fabricated pipework section would be required to be installed on the external section of the top oil line. Figure 4 shows a site-based photograph of the external (left) and internal (right) sections of the top oil line of T1 at the Barrack Road substation.

Figure 4: Photographs of the external (left) and internal (right) sections of the transformer top and bottom oil lines at the Barrack Road substation

Further discussion with an on-site engineer revealed that complete draining of the transformer oil may be necessary prior to retrofit of the top oil line.

3.3 Scarborough Grid Substation

The Scarborough Grid 132/33 kV substation is located in Scarborough in the vicinity of a range of small commercial buildings, an ambulance service building and a NPg satellite office. The proximate heat load assessment identified the manned NPg office as a potentially suitable load for receipt of recovered heat from the substation; however further investigation during the site visit revealed that the extent of the heat demand in this office is insufficient to support a commercially viable investment in a heat recovery system. Further analysis of surrounding loads led to the conclusion that the nearby Tees and North Yorkshire Ambulance Service building has a larger annual heat demand and would therefore be a more suitable load for receipt of recovered heat.

Figure 5 provides an overview of the Scarborough Grid site showing the location of the substation (highlighted in blue) and the ambulance station (highlighted in Orange).

Figure 5 - 3D Render of Scarborough Grid Site (image courtesy of Google Earth®)

The site visit revealed that there is an abundance of space available on site for the installation of the heat recovery equipment. Furthermore, there is an existing auxiliary electricity supply point at the centre of the substation enclosure to which the heat pump and associated pumping equipment could be easily connected. The substation enclosure also benefits from spacious access roads and large entry gates, meaning that transport of equipment into and around the site would be straightforward.

As with the Barrack Road substation, one of the constraining features at the Scarborough Grid site is the presence of live, exposed HV equipment such as overhead lines and bushings. Consequently, heat recovery equipment installed at the site must satisfy minimum clearances and access routes must be developed in order to install the heat recovery system. Figure 6 provides an overview of the Scarborough Grid substation site highlighting access routes and HV clearance zones.

Another key constraint at the Scarborough Grid site is the need for pipework trenching across the substation access road (Zone 5 in Figure 6). The trenching process could be disruptive, restricting access to the site. Discussion with an onsite engineer also revealed that there is a network of electrical wiring beneath the ground at the substation site. As such, consultation of subterranean wiring plans would be essential prior to trenching.

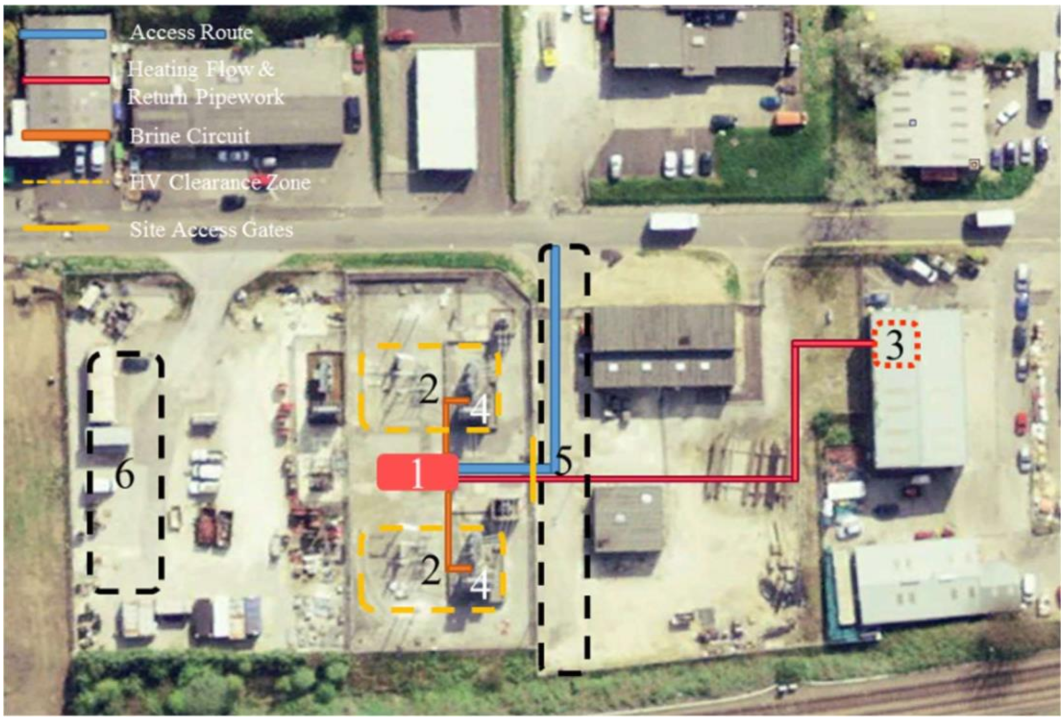


Figure 6 – Scarborough Grid Heat Recovery System Site Plan (image courtesy of Google Earth®)

The figure highlights access routes, heating and return pipework routes, brine circuit pipework routes and HV clearance zones. The numbered items in the figure correspond to the following key locations at the site:

1. The location for the installation of the heat pump, brine circulation pumps (duty and standby), and the heating system circulation pumps (duty and standby). This is the location of the existing auxiliary electricity supply point.
2. High voltage clearance zones.
3. Estimated building plant room location and entry point of heating flow and return pipework into the Tees East and North Yorkshire Ambulance Service Building.
4. Existing air cooling units.
5. Substation site access road (across which trenching would be required).
6. Location of manned NPg satellite office (not present in figure, as built after the satellite image was taken).

The site access route has been developed in consideration of the practicalities of installation of the heat recovery system, aiming to satisfy minimum clearances from HV equipment, whilst maintaining sufficient access to key areas of the site to enable installation. The location of the ambulance service building plant room has been estimated and as such the route of the heating flow and return pipework is subject to change depending on the actual plant room location.

The site visit to Scarborough Grid revealed that it would be possible to integrate the proposed heat recovery solution into the existing transformer configuration, by replacing the top oil pipework with a premanufactured section of pipework containing a three-way valve. Figure 7 shows a site-based photograph of the top and bottom oil lines of T2 at the Scarborough Grid substation.

Figure 7: Photograph of the top and bottom oil lines of Scarborough Grid T2

Discussion with an onsite engineer confirmed that complete draining of the transformer oil may be necessary prior to retrofit of the top oil line. Additionally, a built-in temperature gauge displayed the transformer windings temperatures, observed to be approximately 43ºC during the site visit. The observed windings temperatures were used to inform the technoeconomic appraisal of the substation heat recovery systems as outlined in the following section.

4 Techno-economic Appraisal

The following section outlines the method used to conduct the techno-economic appraisal and presents the results of the cost-benefit assessment.

4.1 Methodology

The methodology used to conduct the techno-economic modelling and develop the cost-benefit assessment followed a multistage process, considering the technical performance of the heat recovery solution and the costs and revenues generated through operation of the system. The stages of the methodology are presented in Chart 1 below.

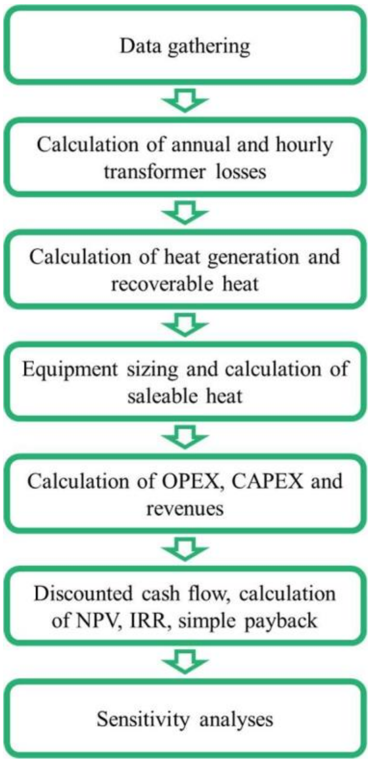


Chart 1: Stages of methodology used to conduct techno-economic modelling and cost- benefit assessment

Bespoke techno-economic models were produced for four different scenarios, modelling heat recovery from one or both of the transformers situated at the Barrack Road and Scarborough Grid sites. Where heat from only one transformer was modelled, the transformer exhibiting the highest losses was used as the basis for the techno-economic model. Specifically, the scenarios modelled are as follows:

1. Heat recovery from Barrack Road T1
2. Heat recovery from Barrack Road T1 and T2
3. Heat recovery from Scarborough Grid T2
4. Heat recovery from Scarborough Grid T1 and T2

In each scenario, transformer top oil temperatures were modelled as equivalent to the temperature of the windings observed at the Scarborough Grid substation, assuming that the residence time of the transformer oil around the windings is sufficient to render the temperature of the oil equivalent to that of the windings. Therefore, for the purposes of this project the top oil temperature in each transformer was estimated to be approximately 43ºC.

Estimation of the top oil temperature and assumption of a heat exchange approach temperature of 10 ºC enabled informed estimates to be made for the temperature of the brine in the heat pump circuit, which were subsequently used to calculate heat pump coefficients of performance (COP – ratio of useful heat out to electrical input) in each scenario. In each techno-economic model, heat pumps were sized at the most economic capacity to utilise the baseload transformer losses, or where limited by the size of the heat demand (e.g. Scarborough Grid scenarios), to meet the total heat demand.

EnergyPro® modelling software was subsequently used to model the operation of the heat pump and thermal store, informing the techno-economic models for each scenario. The outputs of the techno-economic models were used to inform cost-benefit assessments for each of the heat recovery scenarios. Sensitivity analyses were then undertaken to assess the impact of changing CAPEX, heating flow and return (vicariously COP) and heat sale tariffs on project economics. The conditions used in the initial cost-benefit assessment were used as reference conditions in the subsequent sensitivity analyses. The techno-economic models and cost-benefit assessments considered a 25-year project period.

4.2 Results

The results of the initial cost-benefit assessment are presented in Figure 8, Figure 9, and Figure 10, presenting the NPV, IRR and simple paybacks for each of the considered scenarios.

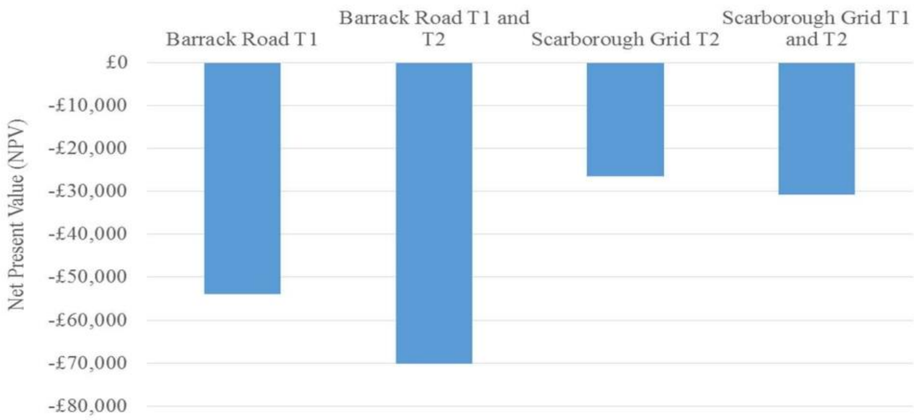


Figure 8 - Net Present Value for each of the heat recovery scenarios

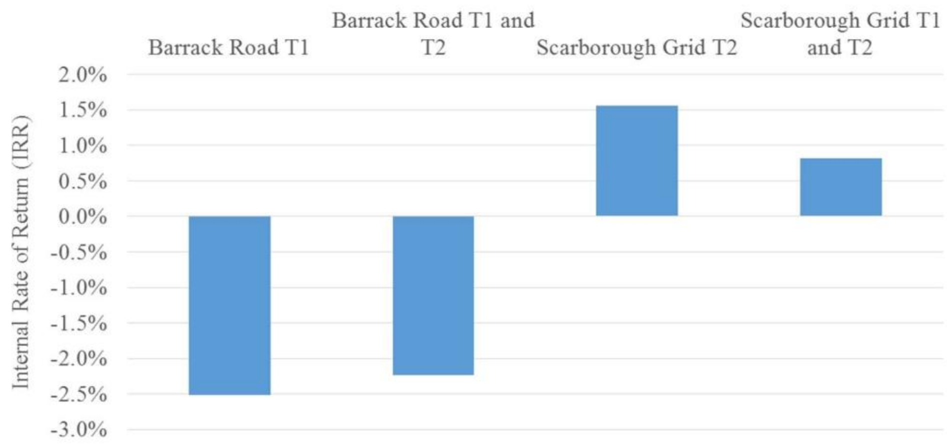


Figure 9 - Internal rate of return (IRR) for each of the heat recovery scenarios

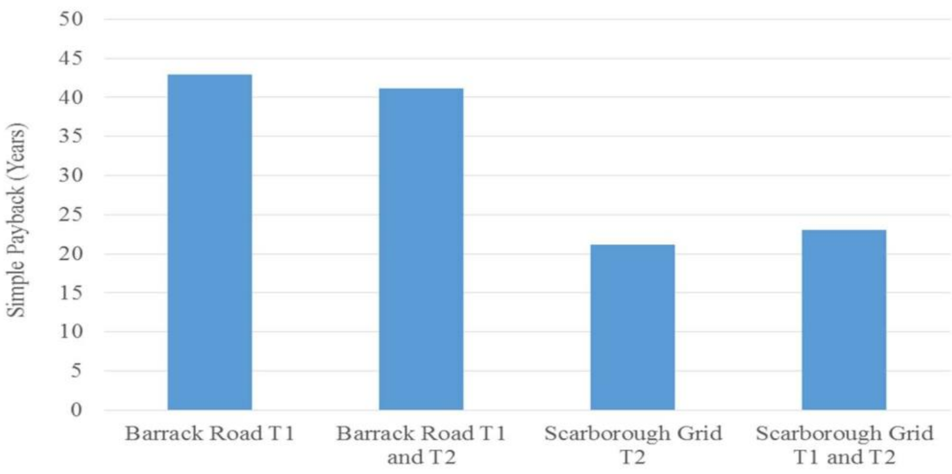


Figure 10 - Simple payback for each of the heat recovery scenarios

Figure 8 shows that the NPV is negative for each of the considered scenarios, indicating that monetary returns do not exceed the initial cost of capital in all cases. Figure 9 shows that the IRRs are negative for the Barrack Road scenarios, but positive for the Scarborough Grid scenarios, indicating that the Scarborough Grid scenarios are the most economic over the considered 25-year project period. Figure 10 reaffirms this, indicating that the Scarborough Grid T2 scenario has the shortest simple payback time.

Contrastingly, Figure 8 and Figure 9 show that heat recovery from the Barrack Road T1 transformer results in the lowest IRR and the highest payback time. Furthermore, high initial capital expenditure limits the economic performance of the Barrack Road T1 and T2 scenario resulting in the lowest NPV of all the considered scenarios over the 25-year project period.

An overview of the estimated quantity of recoverable heat and the estimated quantity of heat deliverable to the identified suitable loads is presented in Table 2.

	Estimated quantity of recoverable heat (MWh/year)	Estimated quantity of heat deliverable to identified load (MWh/year)	Ratio of recoverable heat to heat deliverable to identified load
Barrack Road T1	744	518	70%
Barrack Road T1 and T2	1237	710	57%
Scarborough Grid T2	591	87	15%
Scarborough Grid T1 and T2	1173	87	7%

Table 2 - Overview of estimated quantity of heat recoverable and quantity of deliverable heat in each heat recovery scenario

Table 2 shows that the ratio of heat recoverable to heat deliverable is much greater for the Barrack Road scenarios. This is because the quantity of heat deliverable at Scarborough Grid in our modelled scenario is limited by the extent of the heat demand at the Tees and North Yorkshire Ambulance Service building.

4.3 Sensitivity Analyses

The initial cost-benefit assessment presents a high-level overview of the economic performance of each heat recovery scenario. Sensitivity analyses were conducted to investigate the effect of changing project parameters on economic performance. The following section presents the results of these analyses.

4.3.1 Flow and return temperatures

In heat pump systems, heating flow and return (heat pump inlet and outlet) temperatures dictate the coefficient of performance (COP – ratio of useful heat out to electrical input in). Higher flow temperature operation results in reduced COP as more electrical input is required to enable the heat pump to produce higher temperature flows. The coefficient of performance has major influence on the economic performance of a heat pump system.

Sensitivity analyses were performed to assess the impact of changing these conditions on the economic performance of each heat recovery scenario. The results of these analyses are presented in Figure 11, Figure 12, and Figure 13.

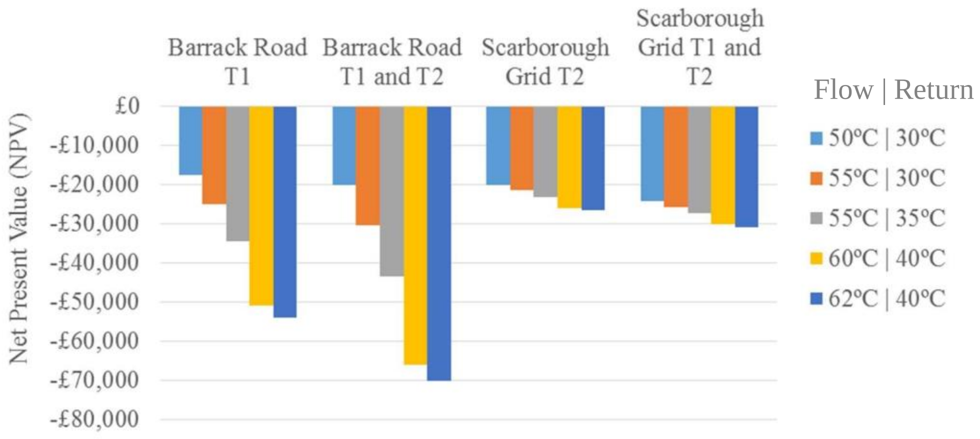


Figure 11: NPV for each scenario under different heating flow and return conditions

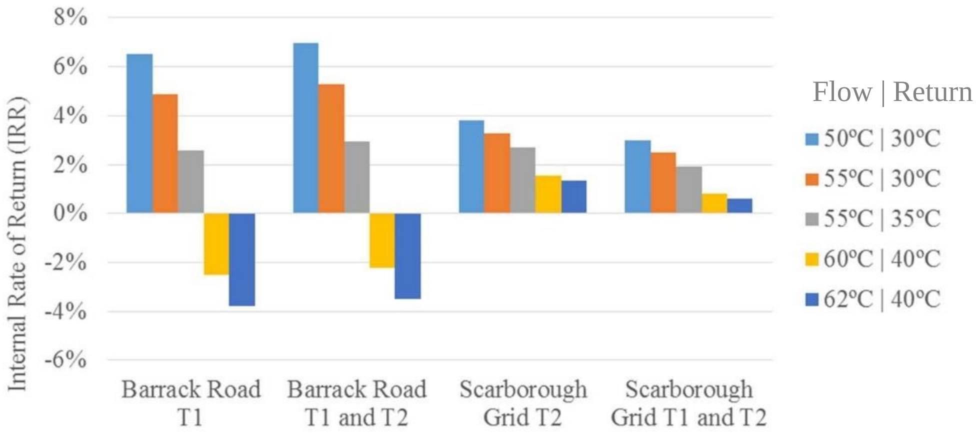


Figure 12: IRR for each scenario under different heating flow and return conditions

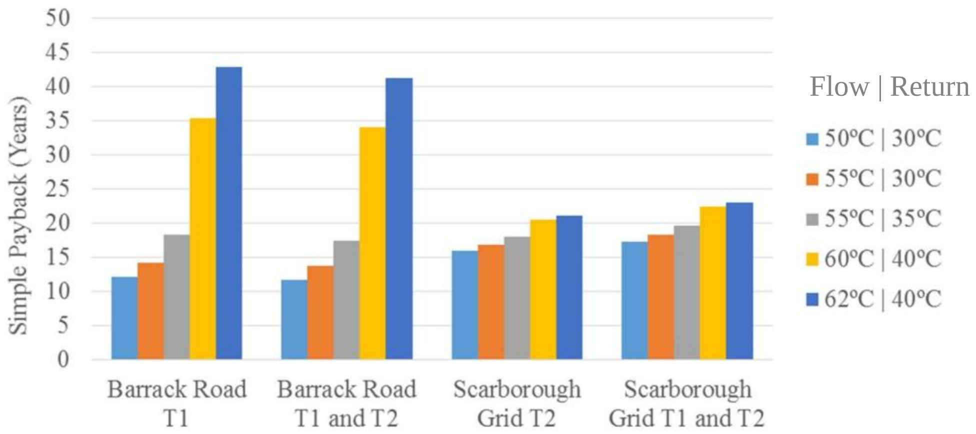


Figure 13: Simple payback for each scenario under different heating flow and return conditions

The figures above show that the economic performance of each heat recovery scenario improves with a reduction in flow temperature. This analysis suggests that lower temperature operation of the heat pump is preferable from an economic perspective. Of those considered, a flow temperature of 50ºC and a return temperature of 30ºC is preferable. Systems operating with flow temperatures less than 50ºC are unlikely to make worthwhile contributions to satisfying heating demands, unless low temperature heating systems such as underfloor heating are installed on the demand side. Furthermore, flow temperatures feeding domestic hot water systems in the UK exceed 60ºC to avoid the risk of bacterial formation, such as Legionella.

One possible solution to these limitations would be to feed the heating flow from the heat recovery system to the common return line to the header of an existing boiler system, where the return temperature could be raised resulting in energy saving through a reduction in boiler load.

4.3.2 CAPEX

This section presents the results of the CAPEX sensitivity analysis. The analysis provides an indication of the resilience of the system to increases/decreases in the cost of the equipment used in the heat recovery solution prior to installation. Sensitivity boundaries of ±20% of the reference, calculated CAPEX values used for each scenario in the initial cost-benefit assessment were used in the analysis. The results of the assessment are presented in Figure 14, Figure 15, and Figure 16.

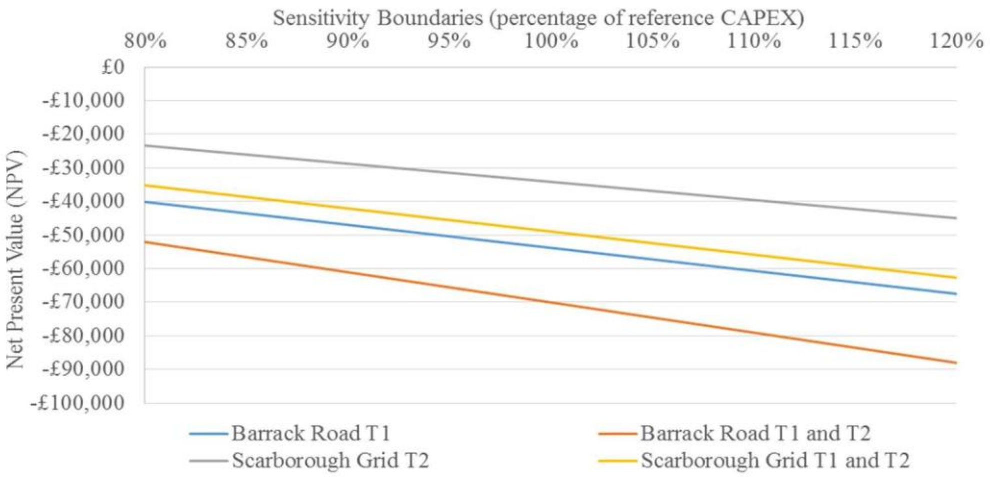


Figure 14: NPV variation with changes in CAPEX

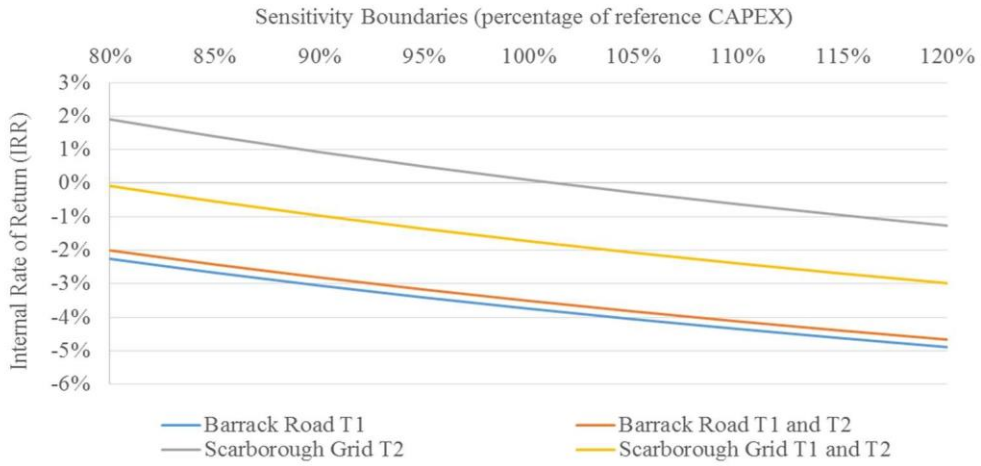


Figure 15: IRR variation with changes in CAPEX

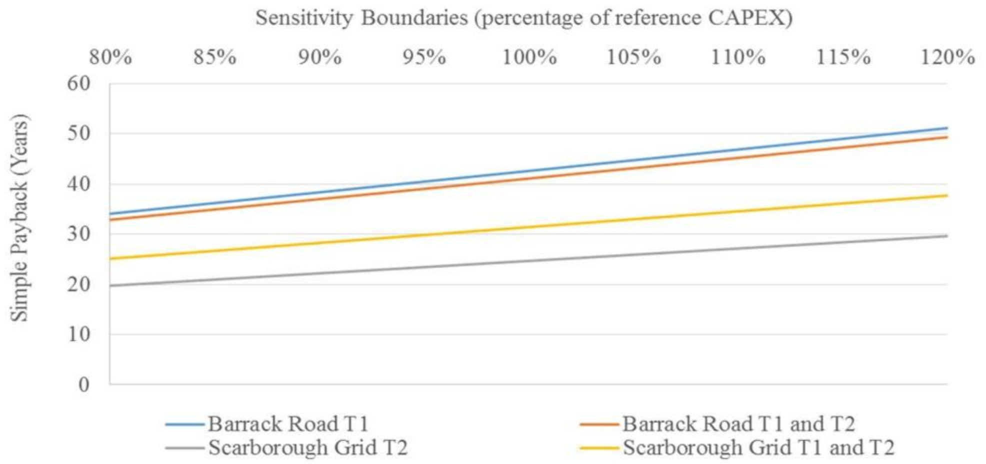


Figure 16: Simple payback variation with changes in CAPEX

The figures show that the economic performance of each scenario improves with a reduction in CAPEX. The results suggest that a 20% reduction in CAPEX could reduce payback times by >10% for the Barrack Road scenarios and by approximately >5% for the Scarborough Grid scenarios. The results show that the Barrack Road scenarios are more sensitive to CAPEX variation than those at Scarborough Grid.

4.3.3 Heat sale tariff

This section presents the results of the heat sale tariff sensitivity analysis. The analysis investigates the effect of changing the heat sale tariff on the economic performance of each scenario. The results of the analysis are presented in Figure 17, Figure 18 and Figure 19.

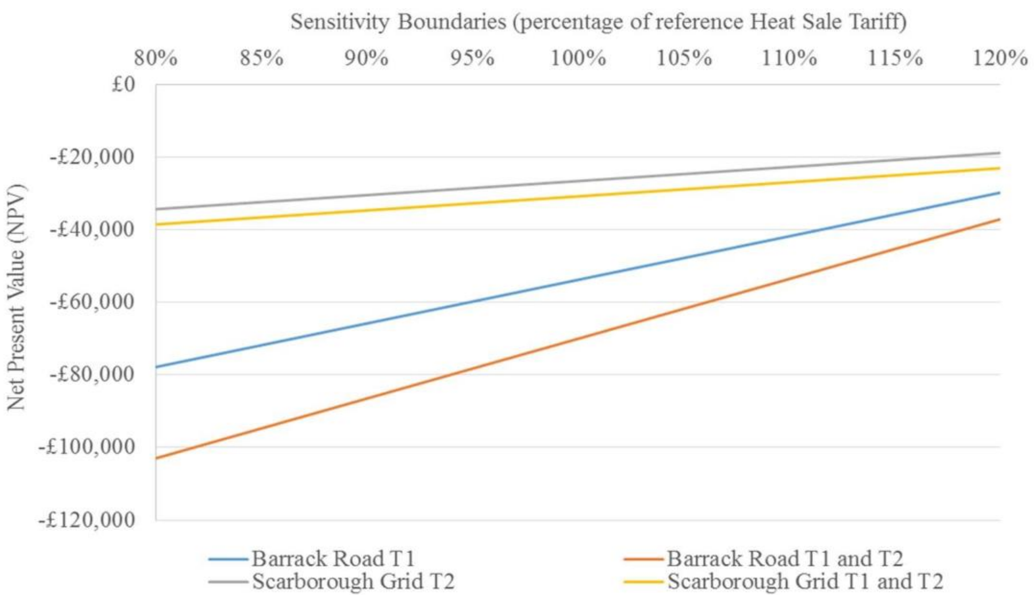


Figure 17: NPV variation with changes in heat sale tariff

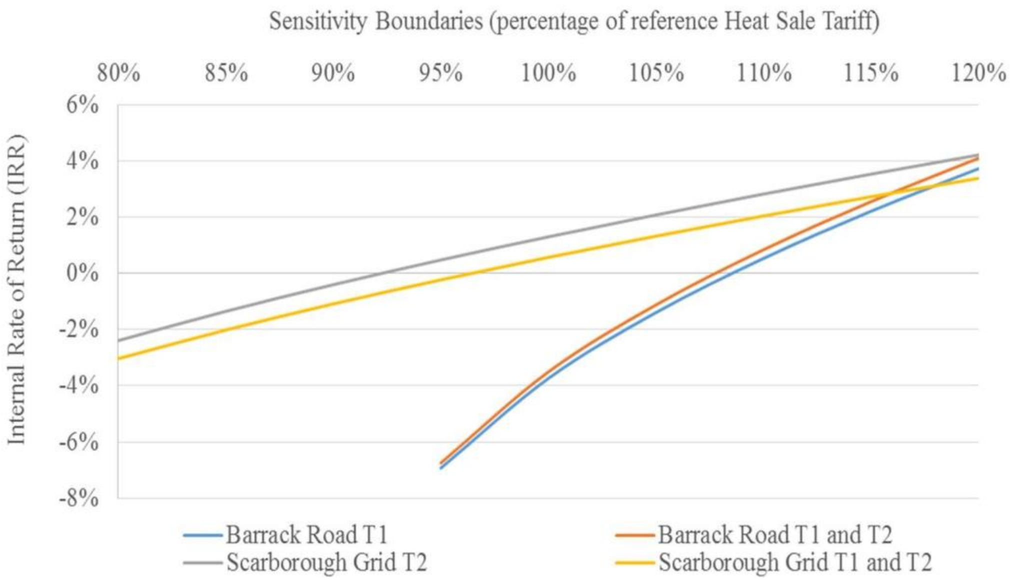


Figure 18: IRR variation with changes in heat sale tariff

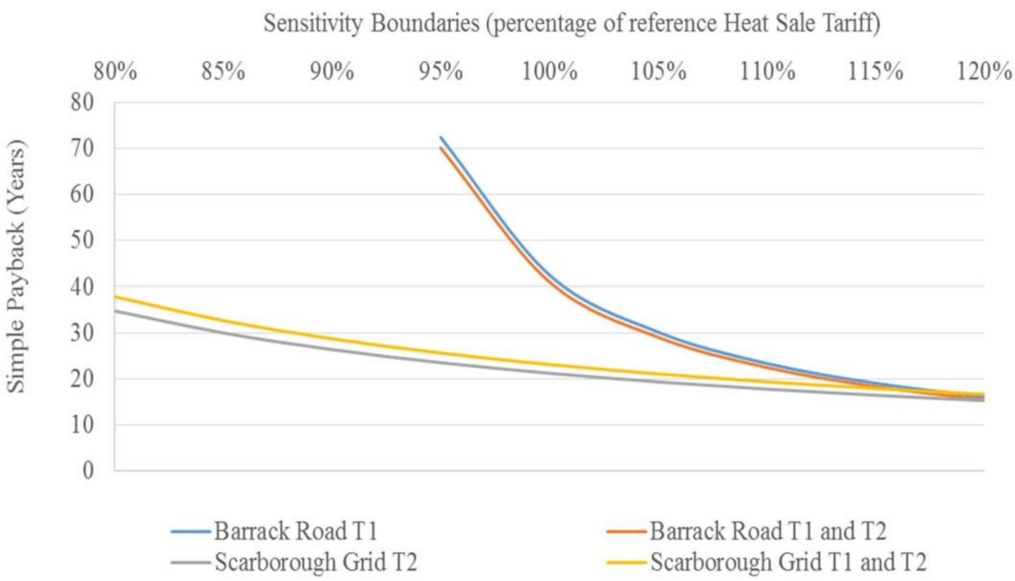


Figure 19: Simple payback variation with changes in heat sale tariff

The figures show that the economic performance of each scenario improves with an increase in the heat sale tariff. It is therefore possible to conclude that heat should be sold at the highest possible tariff in order to ensure maximum project returns; however, the heat sale tariff must remain competitive and in line with current heating tariffs in order to secure a heat purchase agreement. The optimal heat sale tariff represents a compromise between income and market competitiveness.

The figures show that increases in the heat sale tariff result in large increases in IRR and sharp reductions in simple payback for the Barrack Road scenarios, suggesting that a heat recovery system at Barrack Road would be highly sensitive to variations in the heat sale tariff.

A comparison of the tariffs required to breakeven in the discounted cash flow analysis (discounted breakeven rate) and estimated current heat purchase tariffs[3] for the proposed heat loads is listed in Table 3.

Scenario	Heat load	Heat sale tariff required to breakeven in discounted cash flow (p/kWh)	Estimated current heat purchase tariff (p/kWh)
Barrack Road T1	St James' Point accommodation building	3.90	2.69
Barrack Road T1 and T2	St James' Point accommodation building	3.83	2.69
Scarborough Grid T1	Tees and North Yorkshire Ambulance Service building	8.23	4.88
Scarborough Grid T1 and T2	Tees and North Yorkshire Ambulance Service building	8.76	4.88

Table 3 - Comparison of discounted breakeven heat sale tariff and estimated tariffs currently paid by the proposed consumer heat loads

The table shows that in each scenario the tariff required to breakeven in the discounted cashflow analysis exceeds the estimated heat purchase tariff currently paid by the proposed consumer heat loads.

[3] Estimated using national average gas prices including Climate Change Levy, and assumed boiler efficiencies

5 Conclusions

This study aimed to investigate the feasibility of recovering heat from NPg substations, providing a concept technical solution to enable heat recovery from transformer assets and a cost-benefit assessment to assess the economic viability of implementing a substation heat recovery scheme.

Integrated Risk Matrices (IRMs) and Geographical Information System (GIS) models were used to evaluate NPg substations according to a range of assessment criteria, identifying the Barrack Road and Scarborough Grid substations as the most suitable for heat recovery. These substations were taken forward as the subjects of techno-economic modelling, cost-benefit assessment and sensitivity analyses.

A concept technical solution was developed employing an oil-water heat exchange system to recover heat losses from substations and a brine-water heat pump to upgrade water temperature for use in heating systems. The proposed solution works alongside existing air-cooling equipment to ensure transformer functionality and prevent high oil return temperatures.

The results of the cost-benefit assessment suggest that the heat recovery scenarios investigated are not economically viable, indicated by negative project NPVs, low IRRs and long simple payback periods for all scenarios. Subsequent sensitivity analyses illustrated that low initial capital expenditure (CAPEX) and low temperature operation of the heat pump were preferable from an economic perspective.

The sensitivity analyses also revealed that higher heat sale tariffs improved the economic performance of each scenario. This trend was particularly prevalent in the Barrack Road scenario models which showed large increases in IRR and large reductions in payback time, with increases in the heat sale tariff. The results of the study show that in each scenario, the tariff required to breakeven in the discounted cash flow analysis exceeds the estimated tariff currently paid by the proposed consumer heat loads.

Securing a heat purchase agreement with a tariff that is above the scenario discounted breakeven rate could lead to the financial success of a substation heat recovery project; however, procurement of such an agreement would be challenging, as the required tariffs would not be competitive with current market rates.

Two further potential economic viability enhancements are noteworthy for NPg to consider for the future: accounting for potential benefits to NPg of being able to operate at increased loads above the ONAF design limit., and factoring in benefits of reduced ONAF fan power operation.

Appendix B: Substation shortlisting

Project title	LDR Tranche 1 - Transformer Heat Recovery	Job number	260324-00
cc		File reference	
Prepared by		Date	10 May 2018
Subject	Overview of Substation Shortlisting Process		

B1 Introduction

This document presents the results of the proposed shortlisting processes to identify targeted substations for cost / benefit assessment and observational survey. It describes three different methods that utilise transformer loss estimates, local gas consumptions, heat network locations, and visual inspection of possible heat loads.

At the end of this document, a recommendation for next steps is provided.

B2 Method 1

B2.1 Stage 1

The first stage in producing the shortlist of substations to take forward involved ranking each substation in relation to two key criteria, namely;

- The estimated total annual transformer losses, since it is expected that it will be more economic to recover heat from transformers with greater losses.
- The sum of gas consumption within a 1km radius of the substation, since this gives an indication of the heat demand in the vicinity, and therefore potential for use of the recovered heat from the transformer.

As a first step in the shortlisting process, a GIS model was produced, in which substation locations within the NPg network area were represented as nodes. In order to visualise the aforementioned key criteria, the nodes were formatted such that the colour of each node represents the sum of gas consumption within a 1km radius and the size of each node indicates estimated total annual transformer losses. Within this system, substations with high local heat demand and high losses are deemed favourable and appear as large, red nodes; whereas substations with low local heat demand and low losses appear as small, green coloured nodes. A screenshot of this initial stage of the shortlisting process is shown in Figure 20.

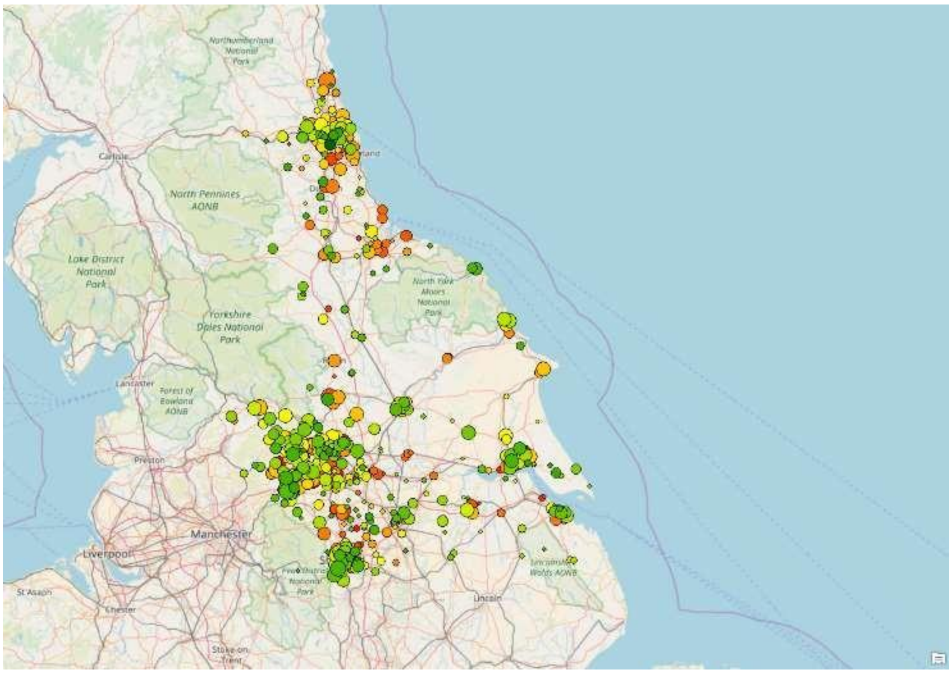


Figure 20 - GIS Based Visualisation of Shortlisting Process

B2.2 Stage 2

In order to identify the most suitable substations to be included in the final shortlist, MS Excel® modelling techniques were used to develop an Integrated Risk Matrix (IRM), informing an overall rank of each substation in terms of the key assessment criteria. Within this matrix, an equal weighting was applied to the rank of estimated total annual transformer losses and the rank of gas consumption within a 1km radius of each substation.

The output was the assignment of an overall ranking to each substation, thus enabling the identification of the top three substations to be included in the final shortlist. The outputs of this IRM analysis are presented in Table 1, with the shortlisted, top performing substations highlighted.

IRM Rank	Substation Name	Estimated total losses per year (MWh/y)	Average heat loss (kW)
1	Harrogate GT3A 132kV	385	43.9
2	Lindley T1	406	46.3
3	Harrogate GT2A 132kV	349	39.8
4	Gosforth GT2 132kV	372	42.5
5	Girlington T1	320	36.6
6	Girlington T2	301	34.4
7	Harrogate GT3B 132kV	241	27.5
8	Harrogate GT1 132kV	240	27.4
9	Bransholme T1	262	29.9

10	Leeds North T1	340	38.9

Table 4 - Substation and Respective IRM Rank

B3 Method 2

A key criterion that could affect the viability of heat recovery from substations, is the proximity of the substation in relation to heat networks. Due to increased pipework costs and thermal losses, the viability of connection to a heat network decreases as distance increases. Although the outputs of Method 1 are sufficient in terms of shortlisting substations in terms of transformer losses and extent of local heat demand, upon analysing the proximity of the shortlisted substations to heat networks, it was clear that all of the listed substations were situated at prohibitive distances from heat network schemes (in excess of 1km).

Consequently, Method 2 acts to incorporate proximity to heat networks as a key assessment criterion in the shortlisting process. The procedure for Method 2 is outlined in this section.

B3.1 Stage 1

The first element of Stage 1 of Method 2 involved revisiting the GIS model and producing a similar GIS model, supplemented with the location of heat networks. The node-based formatting of this new model was also changed such that substation nodes appeared as a uniform size, where node colour indicates the extent of transformer losses, with high losses represented by red colouring and low losses represented by green colouring. Within this new formatting system, the sum of gas consumption within a 1km radius of the substation (Stage 1 Method 1) was disregarded on the basis that this factor is rendered obsolete if the recovered heat from the transformer is to be fed into an existing heat network. The output of Stage 1 of Method 2 is presented in Figure 21.

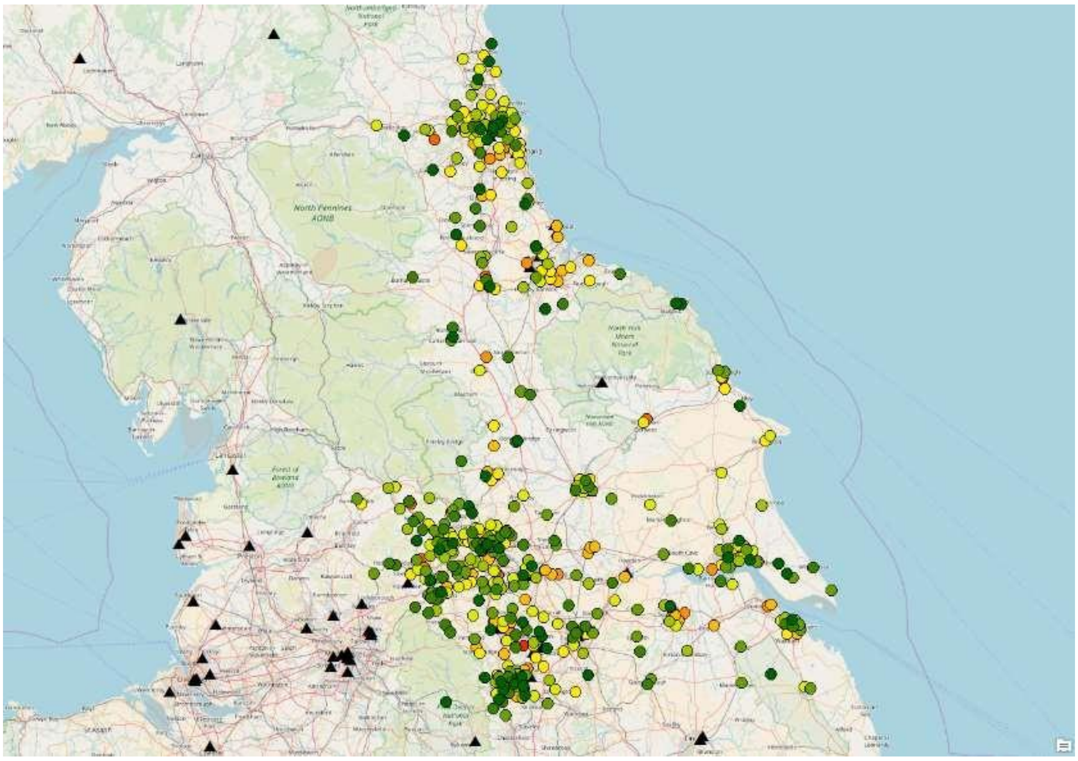


Figure 21 - GIS Model Indicating Substation Locations, Mean Transformer Losses and Heat Network Locations (Heat Network Locations appear as Triangular Nodes)

B3.2 Stage 2

Stage 2 of Method 2 involved producing a shortlist of the substations closest to heat networks. This shortlisting process was achieved by inspecting the GIS model and measuring distances between substations and heat networks. The ten substations closest to heat networks were then identified and taken forward as a preliminary shortlist. The outputs of this stage of the shortlisting process are outlined in Table 2.

Substation Name	Name of Closest Heat Network	Approximate Distance to Closest Heat Network (m)	Mean Transformer Losses (MWh/y)
University T1 33kV	Royal Victoria Infirmary	387	198
Carlton Hill T1	Leeds General Infirmary	594	148
Victoria Street T1	Sheffield University	787	154
Brookfield Street T1	Leeds Yarn Street (Miller Homes)	816	96
Spring Mill Street M1	St Luke's Hospital RAE	820	128
Clarendon Road T1	Leeds Civic Quarter	833	118
Low Road T1	Leeds Yarn Street (Miller Homes)	834	254
Arundel Street T1	Sheffield Hallam University	853	119
Park Hill T1	Sheffield Hallam University	866	98
Longbenton T1 33kV	Freeman Hospital	876	139

Table 5 - Overview of Distances between Substations and Heat Network Schemes for Substations closest to Heat Networks

In order to determine the shortlist of the three most viable substations to take forward as the final shortlist for this Method, MS Excel modelling techniques were used to produce an IRM to determine the overall ranking of each of the substations in the preliminary shortlist in terms of proximity to heat networks and estimated total annual transformer losses. Within this IRM, an equal weighting was applied to the rank of proximity to heat network, and rank of estimated total annual transformer losses. The outputs of this stage of the shortlisting process are presented in Table 3, in which the three best performing substations which constitute the final shortlist are highlighted.

IRM Ranking	Substation Name	Estimated total losses per year (MWh/y)	Average heat loss (kW)
1	University T1 33kV	198	22.7
2	Carlton Hill T1	148	16.9
3	Victoria Street T1	154	17.5
4	Low Road T1	254	29.0
5	SPRING MILL STREET T1	128	14.6
6	Brookfield Street T1	96	10.9
7	Clarendon Road T1	118	13.5
8	Longbenton T1 33kV	139	15.9
9	Arundel Street T1	119	13.6
10	Park Hill T1	98	11.1

Table 6 - Summary of Integrated Risk Matrix Outputs

B4 Method 3

Methods 1 and 2 enable the development of shortlists of substations in relation to:

1. Mean transformer losses and the sum of the gas consumption within a 1km radius of each substation (indicative local heat demand).
2. Mean transformer losses and the proximity of each substation to heat networks.

However, further analysis of the extent of losses experienced by each transformer revealed that the average heat loss per transformer was relatively small for the purpose of connecting to a potential new heat network to serve multiple buildings or an existing heat network. We consider that in each case, the relatively small possible heat supply from the substations would have limited commercial viability.

Similarly, the two methods considered so far do not take into account heat supply and load temperature suitability.

Delivery of recovered heat directly to single adjacent heat loads may however present a more commercially viable option, in the event that existing heating system types and temperatures are suitable. Consequently, another analysis was undertaken to develop a shortlist which assesses mean transformer losses and the proximity of transformers to suitable single adjacent heat loads.

B4.1 Stage 1

Stage 1 of Method 3 involved analysing the outputs of the ranking process undertaken in Method 1, in order to identify the transformers with the highest estimated annual transformer losses. The ten transformers which exhibited the highest annual losses were then taken forward a preliminary shortlist for further assessment in terms of their proximity to suitable heat loads as part of Stage 2.

B4.2 Stage 2

Stage 2 of Method 3 involved reviewing GIS satellite imagery of substation locations alongside higher resolution images in Google Maps®, in order to identify the location of suitable heat loads in proximity of each substation. This process enabled the elimination of substations where no observable possible proximate heat loads were apparent, facilitating the development of a final shortlist comprising the three substations with the highest estimated transformer losses and suitable, proximate heat loads. The outputs of this stage are presented in Table 7, with the outputs of Stage 2 for the Barrack Road 132kV substation presented in Figure 22 and Figure 23.

Ranking	Substation name	Estimated total losses per year (MWh/year)	Average heat loss (kW)	Possible proximate load	Rank within final shortlist
1	Callywhite Lane	531	60.7	Yes	1
2	Scarborough Grid GT2 132kV	491	56.1	Yes	2
3	West Melton SP T1	488	55.8	No	
4	West Melton SP T3	488	55.8	No	
5	Scarborough Grid GT1 132kV	485	55.4	Yes	2
6	Barrack Road GT1 132kV	483	55.1	Yes	3
7	Barrack Road GT2 132kV	479	54.7	Yes	3

Table 7 - Summary of Shortlisted Substations for Method 3

By way of example, Figure 22 and Figure 23 show the proximity of the Barrack Road 132kV substation (cyan node) to St James' Park Football stadium, a potentially suitable heat load with scope for heat recovered from the transformer to be fed into, for example, under pitch heating or space heating systems.

Figure 22 – GIS based Capture of Barrack Road 132kV Substation Location

Figure 23 - Google Maps based Capture of Barrack Road Substation Location

B5 Recommendation and next steps

Upon review of all shortlisting methods, we consider that Method 3 is the most suitable method for shortlisting. Consequently, it is recommended at this stage that the Callywhite Lane, Scarborough Grid 132kV, and the Barrack Road 132kV substations be taken forward as the focus of research.

Notwithstanding this preliminary recommendation, we now propose to update Methods 2 and 3 as follows and consider whether the shortlist should be modified in light of the results:

- Update Method 2 with locations of known planned heat networks, and with simple payback analyses for connection to heat networks.
- Update Method 3 with analysis of possible heat loads.

Following agreement of the shortlisted substations we will:

- Investigate the substations in more detail considering method of heat recovery, possible heat upgrade, and potential heat loads. A cost-benefit assessment will be provided.
- Identify and describe risks to project delivery and operation, and possible mitigating actions.

Appendix C: Overview of Proximate Heat Load Assessment

Project title	LDR Tranche 1 - Transformer Heat Recovery	Job number 260324-00
cc		File reference
Prepared by		Date 21 June 2018
Subject	Proximate Heat Load Assessment	

C1 Introduction

This note presents the results of the analysis undertaken to identify heat loads close to the ten NPg substations with the highest estimated annual losses. At the end of this document, a recommendation for next steps is provided.

The assessment supplements the initial substation shortlisting process[4] where it was concluded that the average transformer heat losses are relatively small for the purpose of connecting to a potential new heat network to serve multiple buildings, or to supply an existing heat network. We consider that in each case, the relatively small possible heat supply from the substations would have limited commercial viability. Delivery of recovered heat directly to *single adjacent* heat loads may present a more commercially viable option. Consequently, 'Method 3' was undertaken to assesses mean transformer losses and the proximity of substations to suitable *single adjacent* heat loads.

The figure below presents an overview of the work undertaken so far and work to be completed.

[4] 2018-05-10 Arup Overview of Substation Shortlisting Process.pdf

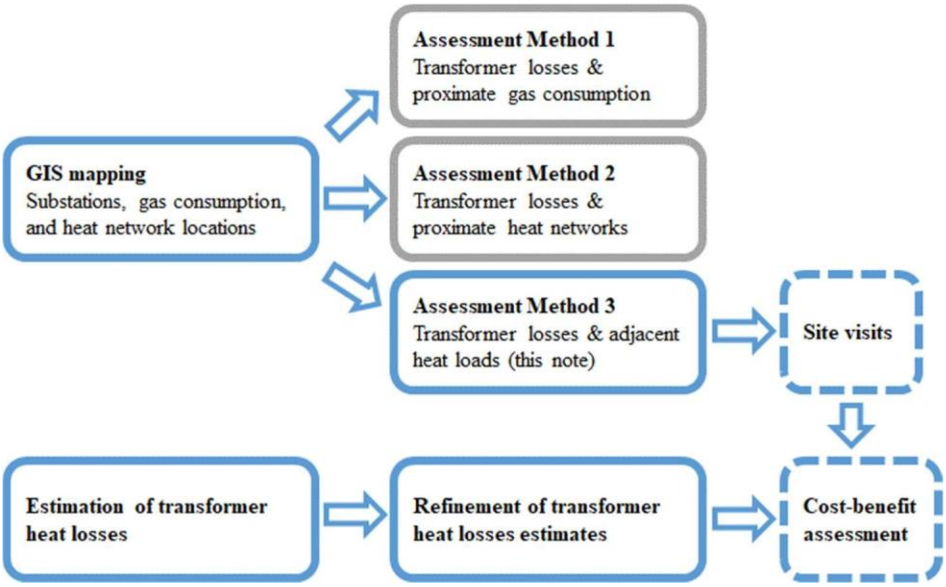


Figure 24: Work undertaken so far (shapes with solid outlines) and work to be completed (dashed outlines).

C2 Method

The heat load assessment was a desktop survey of the areas surrounding the substations to identify potential heat loads. The assessment has focussed on commercial heat loads, and as such, individual residential (dwelling) loads have been disregarded due to expected unsuitability for heat purchase agreements.

The assessment of the suitability of the heat loads was qualitative and comprised consideration of the following aspects, presented in the figure below, in order of importance. The assessment of these aspects for each load was used to determine ‘high’, ‘medium’, and ‘low’ estimated suitability. Summarised reasoning for each building is provided in the results tables that follow.

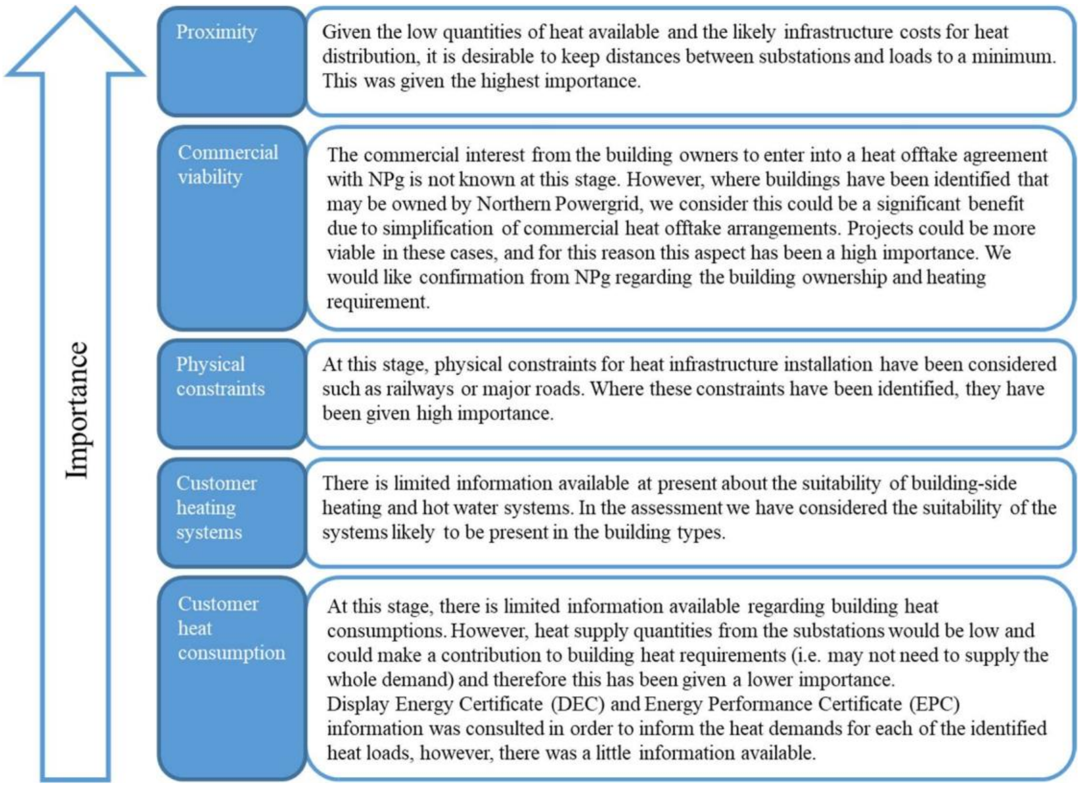


Figure 25: Heat load assessment aspects

C3 Results

The following sub-sections present the results of the proximate heat load assessment. In each case the images indicate the locations of each substation highlighted within blue circles, and proximate heat loads highlighted with white circles. The suitability of each identified load has been assessed using the method presented in the previous section.

C3.1 Callywhite Lane

Based on NPg's estimate of the estimated total losses per year and an adjustment for half-hourly loading profile, the available heat from this substation is estimated at 271 MWh/y equivalent to an average hourly heat supply of ca. 31 kW.

Reference	Name of heat load	Description	Approximate distance from substation (m)	Estimated suitability
1	Building adjacent to transformer (NPg please confirm whether under ownership of NPg)	Brick building adjacent to substation, likely owned by NPg	10	High potential due to proximity and possible NPg ownership.

2	MGS Autos	Automobile garage services (repairs, MOTs etc.)	50	Low due to unlikely heating systems suitability.
3	Lubeline	Retail – industrial equipment	40	Medium; moderately near load.
4	WM Lee ltd	Manufacturer (iron foundry)	100	Low; the foundry is likely to have waste process heat so third party heat offtake seems unlikely.
5	99 Chesterfield Road	Retail – mixed	100	Low; relatively distant load.

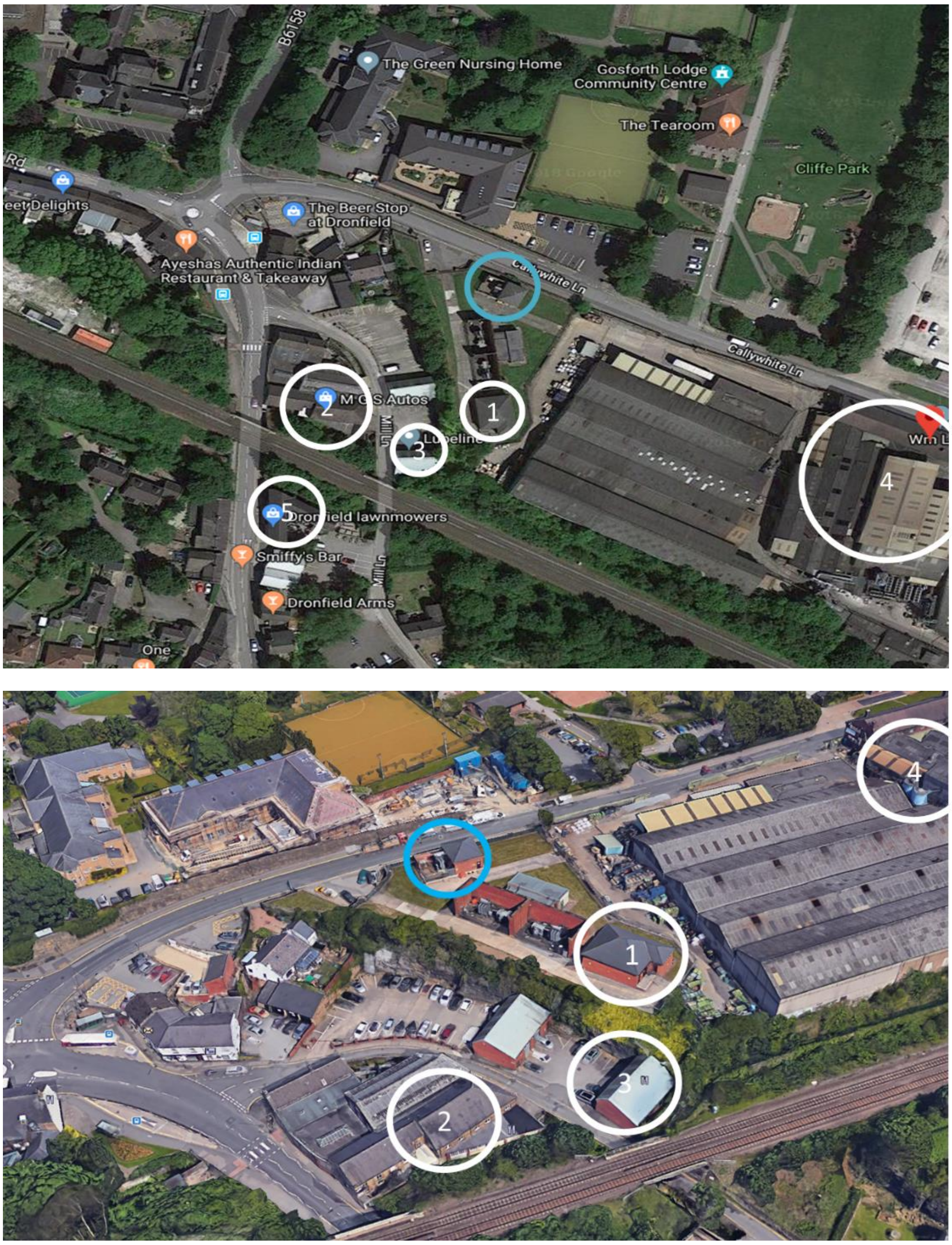


Figure 26: Callywhite Lane substation (blue circle) and proximate heat loads (white circles).

C3.2 Scarborough Grid GT1/GT2 132kV

Based on NPg's estimate of the estimated total losses per year and an adjustment for half-hourly loading profile, the available heat from this substation is estimated at 250 MWh/y equivalent to an average hourly heat supply of ca. 29 kW.

Reference	Name of heat load	Description	Approximate distance from substation (m)	Estimated suitability
1	Electric Centre	Retail – electric goods	20	Medium; near load.
2	Johnston's Decorating Centre	Retail – home goods	25	Medium; near load.
3	Graham Plumbers Merchant	Retail – plumbing supplies	28	Medium; near load.
4	Trans Tools	Retail – tools	45	Medium; moderately near load.
5	HSS Hire	Retail – hire	45	Medium; moderately near load.

Figure 27: Scarborough Grid substation (blue circle) and proximate heat loads (white circles).

C3.3 West Melton SP T1/T3

Based on NPg's estimate of the estimated total losses per year and an adjustment for half-hourly loading profile, the available heat from this substation is estimated at 249 MWh/y equivalent to an average hourly heat supply of ca. 28 kW.

Reference	Name of heat load	Description	Approximate distance from substation (m)	Estimated suitability

1	Large building at centre of site	Large brick building. NPg to confirm whether under ownership of NPg, and heating requirement.	Within 125 metres; exact substation location to be confirmed.	Medium; possible NPg load ownership. Substation location to be confirmed. Heat infrastructure installation may be problematic due to HV operations.

Figure 28: West Melton SP possible heat load (white circle). NPg substation location to be confirmed.

C3.4 Barrack Road GT1/GT2 132kV

Based on NPg's estimate of the estimated total losses per year and an adjustment for half-hourly loading profile, the available heat from this substation is estimated at 245 MWh/y equivalent to an average hourly heat supply of ca. 28 kW.

Reference	Name of heat load	Description	Approximate distance from substation (m)	Estimated suitability
1	Building adjacent to substation	Brick building adjacent to substation, likely owned by NPg.	10	High potential due to proximity and possible NPg ownership.
2	St James' Point	Large student accommodation block (annual heat demand of 1,224 MWh/year)	20	Medium; near load.
3	WA Fairhurst & Partners	Office building	35	Medium; near load.
4	The Cube	Modern office building	40	Medium; moderately near load.
5	St James' Park	Football stadium home to Newcastle United FC	40	Medium; moderately near load.

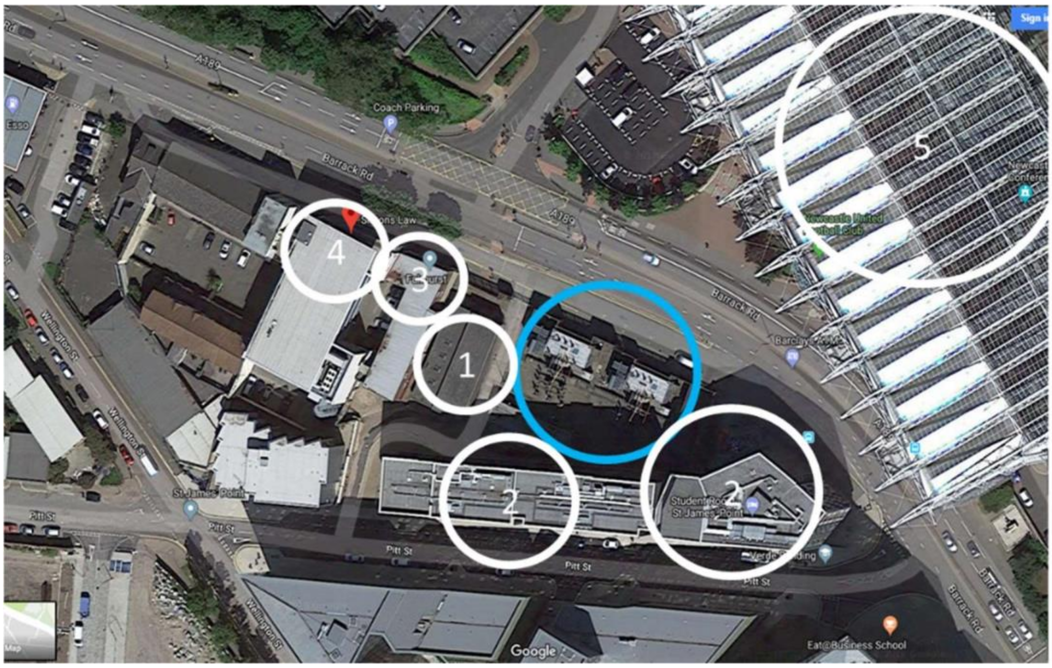


Figure 29: Barrack Road substation (blue circle) and proximate heat loads (white circles).

C3.5 Thornhill

It was assessed that there are no suitable heat loads in close proximity.

C3.6 Beverley T1/T2

It was assessed that there are no suitable heat loads in close proximity.

C3.7 Hull South T1/T2

Based on NPg's estimate of the estimated total losses per year and an adjustment for half-hourly loading profile, the available heat from this substation is estimated at 222 MWh/y equivalent to an average hourly heat supply of ca. 25 kW.

Reference	Name of heat load	Description	Approximate distance from substation (m)	Estimated suitability
1	Mer-Tech Automotive Centre	Garage services building	60	Low; relatively distant load and Hessle Road is a significant barrier.
2	Colt Construction Services	Workshop and offices	65	Low; relatively distant load.
3	Concept Engineering Hull	Concept engineering building	80	Low; relatively distant load and Hessle Road is a significant barrier.

4	DPD Local	Delivery warehouse	100	Low; relatively distant load and Hessle Road is a significant barrier.

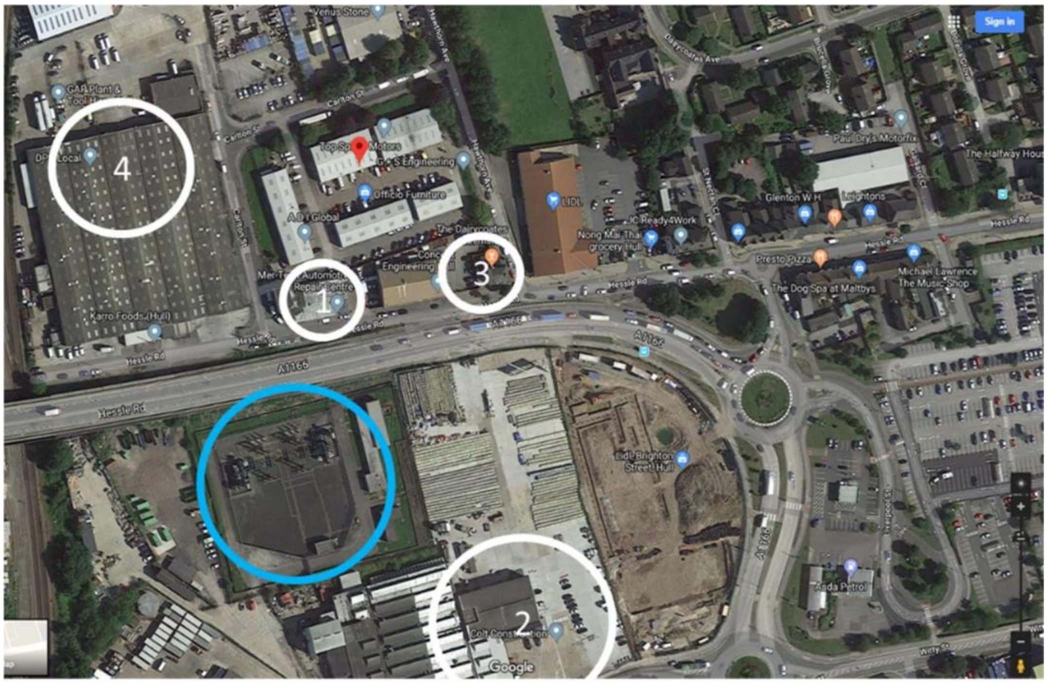


Figure 30: Hull South substation (blue circle) and proximate heat loads (white circles). Hessle Road (A1166) runs between the substation and loads 1, 3, and 4.

C3.8 Silsden GT3

It was assessed that there are no suitable heat loads in close proximity.

C3.9 Brighouse GT2

Based on NPg's estimate of the estimated total losses per year and an adjustment for half-hourly loading profile, the available heat from this substation is estimated at 221 MWh/y equivalent to an average hourly heat supply of ca. 25 kW.

Reference	Name of heat load	Description	Approximate distance from substation (m)	Estimated suitability
1	Aflex Hose	Polymer product manufacturing building	10	Medium; near load.
2	Score Group (Europe)	Engineering building with offices	40	Medium; moderately near load.
3	Arkoni Ltd	Metalwork and glazing product manufacturing building	45	Medium; moderately near load.

4	TOAD Diaries	Paper product manufacturing building	70	Low; relatively distant load.
5	Unit 8 Brighouse Park	Performance glass manufacturing building	75	Low; relatively distant load.

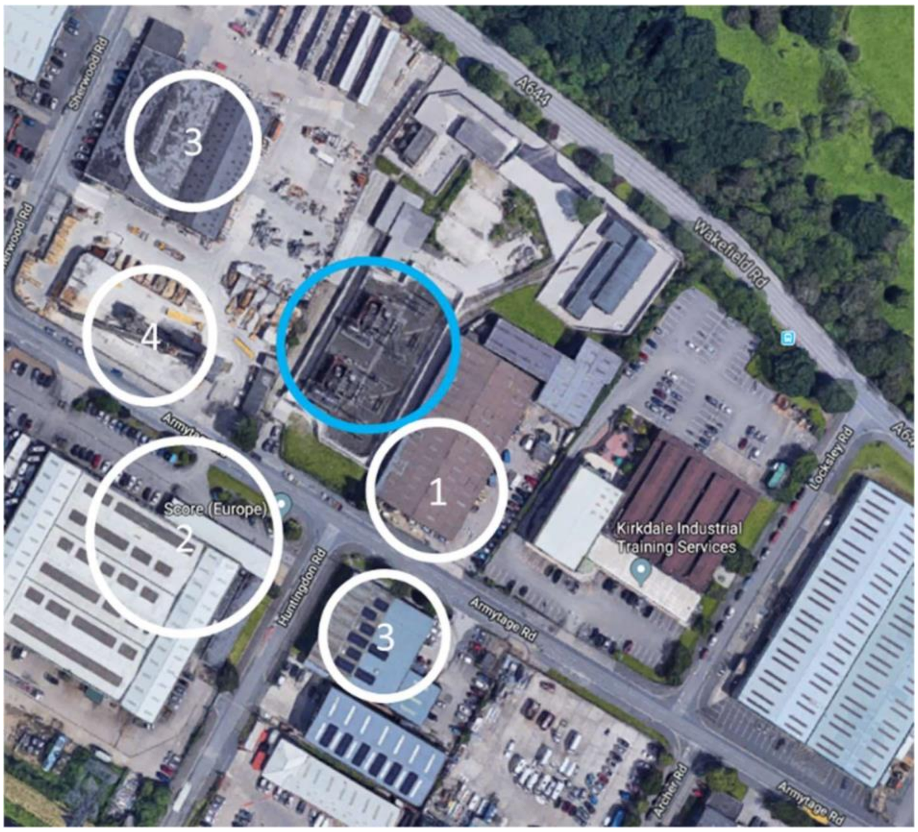


Figure 31: Brighouse substation (blue circle) and proximate heat loads (white circles).

C3.10 Bradford T1/T2

Based on NPg's estimate of the estimated total losses per year and an adjustment for half-hourly loading profile, the available heat from this substation is estimated at 221 MWh/y equivalent to an average hourly heat supply of ca. 25 kW.

Reference	Name of heat load	Description	Approximate distance from substation (m)	Estimated suitability
1	Building adjacent to substation	Brick building adjacent to substation, likely owned by NPg.	10	High potential due to proximity and possible NPg ownership.
2	Farmfoods	Retail – food	30	Low; near load but unlikely heating systems suitability.

3	Aldi	Retail – food	45	Low; moderately near load but unlikely heating systems suitability.
4	Hotel Ibis Budget Bradford	Hotel	72	Low; relatively distant load and Canal Road (A6037) is a significant barrier.
5	Carphone Warehouse	Retail – electronic goods	85	Low; relatively distant load.

Figure 32: Bradford substation (blue circle) and proximate heat loads (white circles).

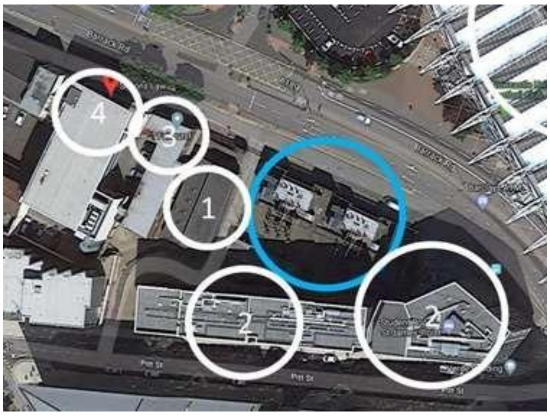
C4 Recommendations & Next Steps

Subject to the request for information below, it is recommended that the following three substations are taken forward in this study.

1. Callywhite Lane at Dronfield.
2. Barrack Road GT1/GT2 132kV at Newcastle upon Tyne.
3. Bradford T1/T2.

Before progressing with the site visits, we would like NPg to:

- Confirm the ownership of the buildings indicated below.
- Indicate the heating and/or hot water requirements for these buildings if possible.

Substation	Name of heat load	Image
Callywhite Lane – Load 1	Brick building adjacent to substation, likely owned by NPg. No.1 in image to the right.	
Barrack Road GT1/GT2 132kV – Load 1	Brick building adjacent to substation, likely owned by NPg. No.1 in image to the right.	
Bradford T1/T2 – Load 1	Brick building adjacent to substation, likely owned by NPg. No.1 in image to the right.