Project SHOES: Secondary Heat Opportunities from Electrical Substations

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ABSTRACT

Through the mechanism of stepping up and stepping down voltages with electrical power transformers, losses in the form of heat occur and are dissipated to the atmosphere. These losses have the opportunity to be recovered and upgraded to help support the thermal demands of buildings as a low carbon secondary heat source. The electrification of heat facilitates the uptake of electrically driven heat pumps that are efficient means of upgrading low temperature heat sources to commonly used temperatures and the employment of low temperature district heating networks enables the transition of these alternative heat sources into the economy. This paper describes the results discovered from an initial investigation on the contribution available from a transformer energy recovery scheme using the Southampton Bulk Supply Point substation and District Heating Scheme as a case study. An annual electrical loading profile on a distribution transformer has been provided and using mathematical modelling the hourly temperatures and losses available for recovery have been estimated and simulated to contribute to the thermal demand of a district heating network. Benefits to the heat sector and asset owner are analysed from the results considering the techno-economic, environmental and social performance with the aim to provide guidance to the engineering community for further in-depth feasibility studies on this waste energy recovery concept.

INTRODUCTION

Globally, renewable energy generation rose by 4% in 2018, however energy consumption increased at nearly twice the average rate of growth. This in turn increased energy-related carbon dioxide (CO_2) emissions by 1.7% to a historic high of 33.1 GtonnesCO_2/year [7.3e+13 IbCO_2/year] (IEA, 2019). It is scientifically proven and accepted that global increases in temperature rise are a result of cumulative long-lived gases and other greenhouse gases (mainly CO_2) caused by anthropogenic behaviour. To help eradicate climate change, a +1.5°C [34.7°F] limit above pre-industrial levels has been set internationally (IPCC, 2018) and in response to this, the UK has committed to tighten its environmental greenhouse gas emission targets to become a "net-zero carbon" economy by 2050 (CCC, 2019).

Heating (and cooling) for buildings and industrial processes is the biggest reason that humans consume energy in our society, and in the UK, it is the single biggest contributor to greenhouse gas emissions, accounting for 44% (693 TWh/year [2.37e+15 Btu/year]) of the final energy consumption in 2017 (BEIS, 2018). Our diverse building stock that supports a variety of heating technologies and desired operating conditions means that the heat sector is the hardest of all to decarbonise. As a result of the ongoing decarbonisation of the national electricity grid, the UK is set to see a major shift to the electrification of heat and also transport (BEIS, 2017), so alleviating pressure on electrical infrastructure through energy recovery becomes more significant.

This study focuses on the losses that occur from electrical power transformers which are used on transmission and distribution grids globally, and the opportunities of recovering the energy from these losses. A mathematical model has been developed with Microsoft Excel to determine the specific losses from a transformer and utilises a heat recovery concept to enable the waste energy to contribute to the thermal demand of a district heating network serving a cluster of buildings. Various scenarios have been modelled using an hourly annual simulation to gain an insight into the benefits of recovering this waste energy for the heat sector and the transformer operator.

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THE HEAT SECTOR

In addition to the vast building efficiency improvements, a diverse variety of low carbon heating technologies that do not rely on the natural gas grid are required in order to decarbonise the sector. The electrification of heat facilitates technologies such as electrically driven heat pumps that have the opportunity to provide heat (and cool) at a least three times the efficiency of direct electric heating or gas driven boilers. A heat pump systems Coefficient of Performance (COP) is dependent on its operating temperatures, and efficiency can be increased by distributing heat at lower flow temperatures. Heat pump technology is an efficient means of raising the temperature from one source to another i.e. air source, ground source or water source, by applying energy on a working fluid (a refrigerant) under the vapour compression cycle (Collie, 1979). There is a current subsidy available from the UK Government to encourage the uptake of this technology (Renewable Heat Incentive – RHI), however heat pumps generally require a much larger capital expenditure (CAPEX) which present economic obstacles for projects.

Waste Heat

Heat that is otherwise rejected as a by-product from industrial and commercial activities along with infrastructure occurs globally, however through a process of heat recovery, the thermal energy can be captured and re-used as a secondary heat source for building space heating and domestic hot water production. As identified by the Mayor of London, waste heat sources are generally of a lower temperature than required and can also be remote from thermal demands (Mayor of London, 2013). To overcome this, heat pumps can efficiently increase the energy to commonly used temperatures.

District Heating Networks

Currently around 2% of UK's heat demand is provided by district heating networks, and a number of studies have concluded that in order for the UK to meet its emissions targets cost effectively, district heating (and cooling) networks are required to provide at least 18% of the UK's heat demand effectively (The Committee on Climate Change & Imperial College London, 2018). This percentage shall only increase as emission targets are tightened. These networks can permit the connection of secondary heat sources by providing a thermal transmission link to multiple demands, that also reduces plant capacity as a result of diversity across multiple buildings types and consequently are most suited to areas of high heat density. Most heat networks in the UK and Europe are of the 2nd and 3rd generation (2GDH and 3GDH) and operate at flow temperatures of +70^{o}C [158^{o}F] with basic metering and monitoring control. Lower operating temperatures enable higher efficiencies of certain heat sources, such as heat pumps, and promote the uptake of lower temperature recycled heat. Additionally, achieving a low design return temperature, reduces peak volume flow rates that result in smaller distribution pipes and losses (CIBSE & ADE, 2015). The 4th Generation of District Heating (4GDH) was defined by Henrik Lund et al. where they identified that the energy community has the technology available to develop smart thermal grids as an interlinked synergy. The authors described that this could be achieved by lowing the flow temperature below 70^{o}C [158^{o}F] with intelligent metering and advanced controls including weather forecasting, enabling connection and communication on to the other energy grids (Lund, et al., 2014). 4GDH enables efficient contribution from waste heat recovery requiring less energy input to offset traditional fossil fuel heat production. Further to this, an arising concept of 5th Generation District Heating (5GDH) with ultra-low distribution temperatures that are maintained below 50^{o}C [122^{o}F] and can be as low as ambient temperatures, could be favourable for thermal support from utilised recovered energy sources. 5GDH have the capability to become 2-way networks where consumers become prosumers and are able to sink or reject (provide heating and cooling to their buildings) energy to the network through building located heat pumps in lieu of central heat pumps (Lund, et al., 2018). This study focuses on the contribution available from transformer waste energy recovery to 4GDH, however it is recognised that the application could be suited to future 5GDH schemes.

POWER TRANSFORMERS AND THEIR THERMAL CHARACTERISTICS

Electrical power transformers are installed outside within specific land area, subterranean or within buildings, the transformer and associated switching gear are known as a substation. Globally they are used across electrical transmission and distribution grids to maximise efficiency where transporting electricity by providing a mechanism to step up and step down the supply voltage.

Transformer Losses

Two types of losses occur from this transforming process, these are known as no-load losses and load losses. No-load losses are made up of a mixture of hysteresis losses and eddy current losses. Under a no-load operation the transformer is energised to enable power to be delivered when required, and so a voltage is constantly applied to the primary windings. This induces currents in the iron core itself and through magnetisation and de-magnetisation from the alternating field hysteresis losses occur. Friction and subsequently heat is generated as a result of the molecules resisting the magnetisation which contributes to 50-80% of the no-load losses. Eddy current losses are caused by the magnetic flux inducing currents in the transformer core. The magnetic fields that surround the core create an induced current at a 90^{o} angle to the flux. As current flows through primary and secondary windings, load losses, otherwise known as copper losses occur. The load losses are generated through the resistance of the copper windings and are proportional to the flow of the current squared. The sum of the no-load losses and load losses are the total losses from a transformer (Kennedy, 1998). Transformers constantly have some quality of losses, whether or not under a load and consequently this heat is to be dissipated to protect the life of the equipment.

As part of this study a range of manufactures name plate data has been gathered to assess the losses from a variety of capacities and have been averaged to derive a kW/KVA [kBtu/KVA] losses factor to develop a tool to estimate the losses on a transformer of a desired capacity as a function of the connecting loading.

Table 1. Mean Transformer Name Plate Losses Factor

	Load Losses p.u.	No-load Losses p.u.	Total Losses p.u.
Mean Transformer p.u. Losses	0.00593 (0.59%)	0.00083 (0.083%)	0.00676 (0.67%)

Transformer Temperatures

Due to the losses associated within the windings and the core, the transformer begins to heat. These temperatures are typically controlled by heat dissipation to the external environment, and generally over a capacity of 1.5MVA use a natural or forced body of liquid such as mineral oil to aid with this process (Faulkenberry & Coffer, 1996). The temperatures experienced within transformers are a function of the loading and are influenced by the internal and external cooling mediums along with the construction materials. This study primarily focuses on liquid immersed transformers, where the highest temperature within the transformer occurs in the windings, defined as the hot spot temperature. Measurements have shown that the hot spot temperature is found to be 15^{o}C [59^{o}F] above the top liquid temperature, and the specific rated temperature limit in accordance with British Standard BS IEC 60076 Part 2 is determined at 78^{o}C [172.4^{o}F] above the external cooling medium temperature (BSI, 2018). It is commonly found that transformers can be overloaded during emergency conditions where this temperature is exceeded (BSI, 2011), and it can be highlighted that transformers could therefore benefit from heat recovery/enhanced cooling to increase emergency overloading limits. Typically, the top oil temperature rise above ambient conditions with forced oil circulation is in the order of 40^{o}C [104^{o}F] (Langlois-Berthelot, 1960).

PRACTICAL ASSESSMENT FOR TRANSFORMER HEAT RECOVERY

The position of an electrical power transformer on a grid will determine the viability of heat recovery and whether this location is within a suitable distance from an adjacent building or the proximity of an existing or future heating network. It is found that typically Grid Supply Point (GSP) substations are too remote to utilise heat recovery for building demands, although in countries such as Denmark where there are established thermal transmission networks the feasibility may be likely. Large Primary or Bulk Supply Point (BSP) transformers however are more susceptible to be located in close proximities of urban areas and be of a size to generate advantageous quantities of energy. It has been determined that if the annual electrical loading on a transformer is circa 40% of the rated capacity and if 80% of these losses are recoverable, then a rated 25MVA capacity transformer approximately has an average 50 kW [172 kBtu] of heat available (320 MWh/year [1.09e+9 Btu/year]) with a upgrade from a heat pump to commonly used temperatures. This estimation shows transformers would typically be required to be of a capacity of 25 MVA and above to develop a commercial business case for energy recovery. Based on an approximate quantity and associated capacities of the UK substation fleet, the estimated average energy available for recovery has been determined in Table 2.

Table 2. UK Substation Fleet Heat Loss

Total Quantity of Transformers > 25MVA	1,711
Average Total Transformer Losses (40% loading)	184 MW [6.28e+8 Btu]
Usable Heat Output (with heat pump uplift to 70°C [172.4°F], SCOP 3.2)	263 MW [8.97e+8 Btu]
Annual Secondary Heat Available at 70°C [172.4°F]	1.84 TWh/year [6.28e+12 Btu/year]

HEAT RECOVERY CONCEPT

Heat recovery could be implemented to various transformer cooling methods either as a retrofit system or engineered into the design of a new transformer. Subterranean transformers could provide an advantage for heat recovery due to their underground enclosed locations. This could suit the application of an air-cooling refrigeration system that would force a cold air stream across the transformer utilising a shell and tube condenser that acts as a mechanism to transfer the energy to a circulated water loop. An advantage to this concept is that it would require no intrusive modifications to the transformers proprietary cooling method, however due to the low specific heat capacity of air, the energy recovered would be limited to spatial constraints as well as transformer capacity.

A further concept has been advanced from an outline in a previous academic study carried out on the management of electricity distribution network by Imperial College London & Sohn Associates losses (2014). The heat recovery/cooling concept utilises the immersed liquid cooling medium used within transformers. By introducing a heat recovery scheme via an oil to water heat exchanger the cooling method would be recognised as Oil Forced Air Forced/Oil Forced Water Forced (OFAF/OFWF). The advantages to this concept are the high transfer rate of the losses to the oil, and subsequently the water, with the potential to provide a continuous source of heat. This concept has been developed into the numerical assessment model and proposes to employ the following control logic.

i. Under an electrical loading on the transformer heat is transferred into the oil. The heat subsequently rises to the top oil which is pumped through pipes to a three-way valve outside of the transformer directing the hot oil to an oil to water heat exchanger.
ii. A water pump circulates cooling water to this heat exchanger where the energy is transferred to the cooling loop, which in turn reduces the temperature of the oil.
iii. A water to water heat pump (WSHP) utilises the energy transferred to the water loop and upgrades it to commonly used heating temperatures, and subsequently provides cooling back to the water loop.
iv. The oil and water circulation pumps operate under a variable volume flow in proportion to the transformer loading, maintaining a water loop of temperature of 12/20°C [53.6/68°F] flow and return, which results in a constant COP that is determined by the WSHPs evaporating and condensing temperatures.
v. The oil is then directed to an air cooler or radiator bank where it's temperature may reduce further. If the oil temperature is above a threshold, cooling fans will operate to reduce this further.
vi. A heating pump circulates the heating water to a thermal store. If the thermal store becomes fully charged then the heat pump shall not operate and the three-way valve will direct the oil straight to the air cooler or radiator bank.

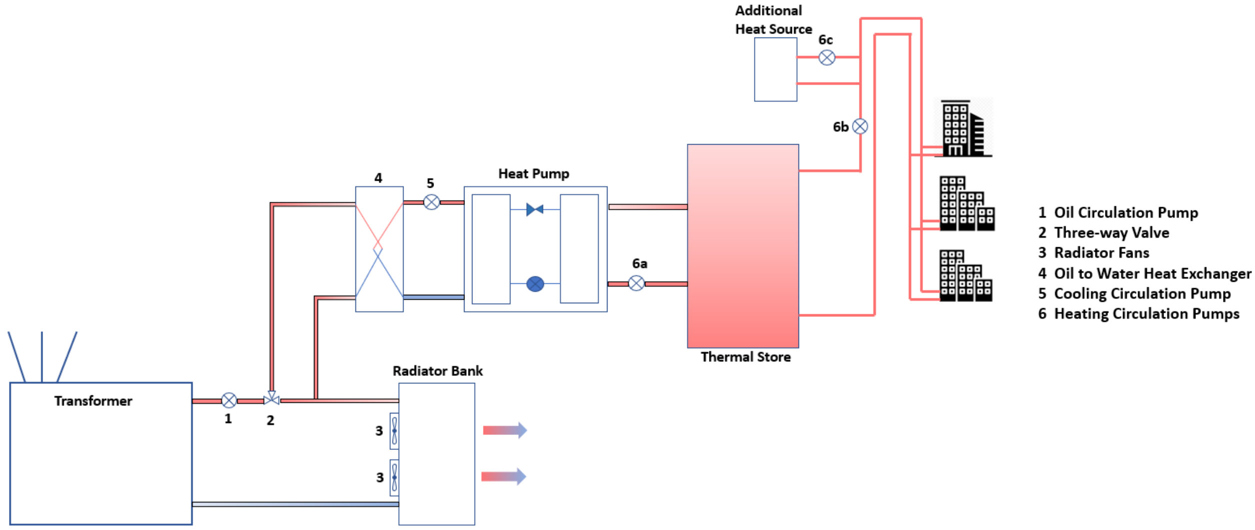

Figure 1. OFAF/OFWF Transformer Heat Recovery Concept Schematic

HEAT RECOVERY MODELLING SCENARIOS AND INPUTS

A case study has been set in the UK city of Southampton, where there is an existing district heating network and a high heat demand density (on average greater than 120 Tj/km² [1.22e+9 Btu/ft2] (Heat Roadmap Europe, 2018)). A heat recovery simulation has been based on a 90MVA 132/33kV OFAF transformer (Transformer T1) that is located at the Southampton BSP substation. Transformer T1 is one of two, where the loading is shared for security and resilience on the network and heat recovery has only been modelled on one of the two transformers to retain. Initial modelling has been based on the contribution available from Transformer T1 to the Southampton District Heating Scheme, which is located approximately 150 metres [492 ft] from Transformer T1 keeping heat distribution pipes from the recovery system to the energy centre at a minimum. The city-wide 3GDH network has a peak thermal demand of 18 MW [61.42e+6 Btu] and a minimum of 2 MW [6.82e+6 Btu] at flow and return temperatures of 80/50°C [176/122°F].

A further case study has been developed from a heat demand assessment of a cluster of newly developed buildings. The cluster of buildings for the modelling purposes have been assumed as 75No. residential apartments, 21,000 m² [226,042 ft²] of commercial office and retail space. The space heating and hot water demands are based on modern construction standards and the space heating demand has been prorated against external ambient temperatures from the CIBSE Southampton DSY Current weather file (2016). Likewise, the hot water usage has been assigned to a daily profile and projected across the year. The heat demand assessment for the cluster of buildings results in a maximum thermal demand on the network of 1.8 MW [6.14e+6 Btu] which includes for 15% distributional losses. A likely development of this nature could be situated at a location 800m [2625 ft] from the Southampton BSP substation. A range of modelling scenarios have been undertaken to enable a techno-economic comparison of the heat recovery scheme and it has been recognised that an Air Source Heat Pump (ASHP) would provide the most suitable comparison when considering future heating technology projections. The heat recovery concept from Transformer T1 has been based upon the oil to water concept described above and the model has been configured to enable the WHSP to provide the first stage of heating by charging a thermal store which supplies the heating networks return. A primary heat source has been modelled to top up the load during times of peak demand. Through sensitivity analysis the optimum thermal output of the WSHP has been determined and modelled as 500kWth [1.71e+6 Btu] based on R171 refrigerant (NH_3 Ammonia) with a 25,000 litre thermal store. This optimum size heat pump for the rated transformer capacity limits the size of the heat exchangers.

An annual hourly loading profile on a 60MVA 132/33kV OFAF transformer that is one of two at a UK BSP substation has been provided by Electricity North West for the purpose of this study. As a function of the loading profile, the total losses, top liquid and hot spot temperatures have been estimated for Transformer T1.

The economic assumptions within the model are based upon a 25-year life cycle costing scenario with a discount factor of 3.5%. The sale of heat from the heat network is assumed at a rate of 0.079 £/kWh [0.269 £/kBtu] and the sale of heat from the asset owner to the heat network has been based upon 0.02 £/kWh [0.06 £/kBtu]. Electricity and natural gas supply prices and carbon intensity factors serving the heat raising equipment have been considered as 0.12 £/kWh [0.41 £/kBtu] and 0.02 £/kWh [0.06 £/kBtu] and 0.233 kgCO_2/kWh [1.74 IbCO_2/kBtu] and 0.210 kgCO_2/kWh [1.58 IbCO_2/kBtu] respectively. The seasonal COP (SCOP) of the modelled WSHP is derived from the operating conditions and the ASHP SCOPs have been gathered from manufactures data with an average external ambient temperature of 12.5°C [54.5°F]. When the heat pumps operate under conditions that results in a SCOP greater than 2.5 they are eligible for the RHI tariff. The current WSHP tariff is applied at 0.0956 £/kWh [0.3262 £/kBtu] for the first 15% of the year and 0.0285 £/kWh [0.0972 £/kBtu] for the remaining and the ASHP tariff of 0.0275£/kWh [0.0938 £/kBtu] (Ofgem, 2018). Initial plant CAPEX and maintenance operational expenditure (OPEX) has been applied from a study that was carried out on the performance of district heating networks by Aecom (2015). The modelling scenarios and operating conditions are identified in Table 3.

Table 3. Modelling Scenarios

Scenario	Description	Network Heating Flow and Return Temperatures	Seasonal COP	WSHP Evap. and Cond. Temperatures
1	4GDH Gas Boiler Base	70/40°C [158/104°F]	0.91	n/a
2	4GDH ASHP	70/40°C [158/104°F]	2.0	n/a
3	4GDH WSHP & ASHP	70/40°C [158/104°F]	3.39 & 2.0	10/72 °C [50/162°F]
4	4GDH WSHP & Gas Boiler	70/40°C [158/104°F]	3.39 & 0.91	10/72 °C [50/162°F]
5	4GDH ASHP	65/35°C [149/95°F]	2.89	n/a
6	4GDH WSHP & ASHP	65/35°C [149/95°F]	3.78 & 2.89	10/67 °C [50/153°F]
7	4GDH WSHP & Gas Boiler	65/35°C [149/95°F]	3.78 & 2.89	10/67 °C [50/153°F]

Calculation Methodology

The main modelling calculations are summarised below. Eq. 1 determines the transformer load losses.

$$P_l = \left(\frac{\%\ of\ loading}{100}\right)^2 . P_{lr} \qquad \text{(Eq. 1)}$$

The top liquid temperature is given by Eq.2.

$$\theta_{od} = \theta_a + \theta_{os}\left(\theta_{oid}\left(\frac{1+R+K^2}{1+R}\right)^x - \theta_{os}\right).1 - \left(e^{\left(\frac{-\tau}{(K_{11}.\tau_o)}\right)}\right) \qquad \text{(Eq. 2)}$$

The energy balance in Eq.3 represents the transfer of energy across the system.

$$P_t = \dot{m}_o . cp_o . (t_{of} - t_{or}) = \dot{m}_w . cp_w . (t_{wr} - t_{wf}) \qquad \text{(Eq. 3)}$$

The heating output available from the heat pump can then be determined by Eq.4.

$$Q_h = \dot{m}_r . (h_2{}' - h_3) \qquad \text{(Eq. 4)}$$

After the cooling has been provided from the heat pump the oil temperature can be defined from Eq.5.

$$t_{or} = t_{of} - \left(\frac{Q_c}{\dot{m}_o . cp_o}\right) \qquad \text{(Eq. 5)}$$

The heat pumps COP in heating mode is given by Eq.6.

$$COP_h = \left(\frac{Q_h}{W_{in}}\right) \qquad \text{(Eq. 6)}$$

MODELLING RESULTS

The average annual losses from Transformer T1 have been estimated at 145kW and an average top liquid temperature of 30°C [86°F]. Through an uplift with a WSHP, it is estimated that an average heating output of 195 kWh [665 Btu] at 80°C [176°F] is available, annually providing 1,323 MWh [4.5e+9 Btu/h]. As a standalone secondary heat source, the modelling results estimate that 4.5% of the Southampton City District Heating demand could be met by the energy recovery concept from Transformer T1. It is recognised that this available contribution would suit the application of multiple secondary heat sources serving the network in order to provide favourable financial and environmental savings to the Southampton City District Heating Scheme. On the other hand, where the energy recovery concept supports a cluster of buildings with a smaller demand, it is estimated that 43% of the annual thermal demand could be provided from this secondary heat source.

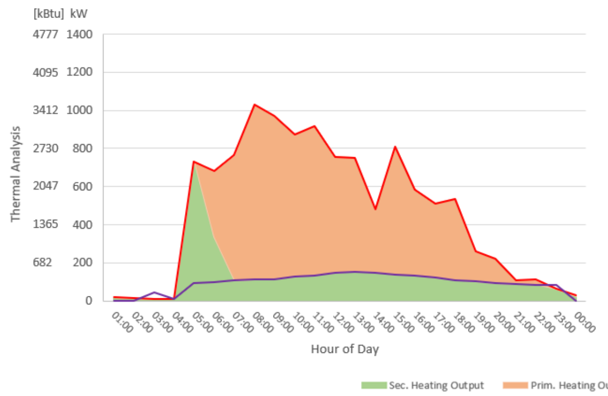

Figure 2. Secondary Heat Contribution January Day

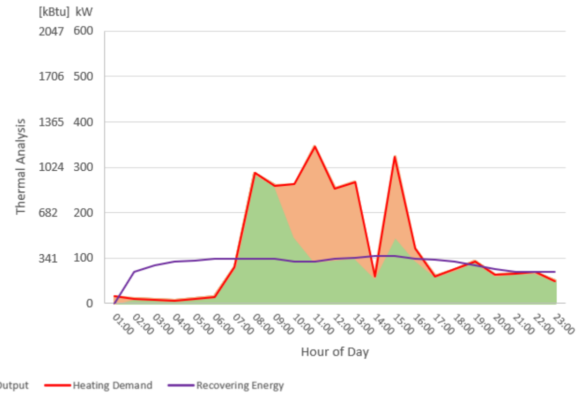

Figure 3. Secondary Heat Contribution July Day

Figure 2 shows that during the winter month of January the secondary heat recovered and supplied from Transformer T1 contributes to 28% of the daily thermal demand and Figure 3 shows that this increases to 67% in the summer month of July. From both figures the operational energy recovery is shown to be maximised through the thermal store allowing energy recovery during times of low demand and enabling an increased output from the store under demand. The economic and environmental performance of the energy recovery scheme has been assessed from the prospective of the heating distributor (network operator) and it can be seen from Figure 5 that scenarios S2 and S3 provide a negative NPV. This is due to the higher operating temperature of the heating network at 70°C [158°F] that consequently results in the ASHP SCOP >2.5 making it un-eligible for the RHI tariff. From a techno-economic prospective, the operating temperatures of heating networks need to be reduced to below 70°C [158°F] to enable heat pumps to become financially feasible heat sources. Figure 5 identifies that scenario S5 is the most financially favourable because of the RHI tariff gained on the ASHP along with no CAPEX from the WSHP and heat recovery equipment. Whereas, scenario S7 has the lowest cost intensity of the heat provided due to the low fuel prices of natural gas. It is more financially beneficial to support the heat network with the WSHP and gas boiler when compared to the WSHP and ASHP scenario as the initial CAPEX is reduced. Economic and spatial constraints are both barriers to a heating network supported by a WSHP and ASHP array.

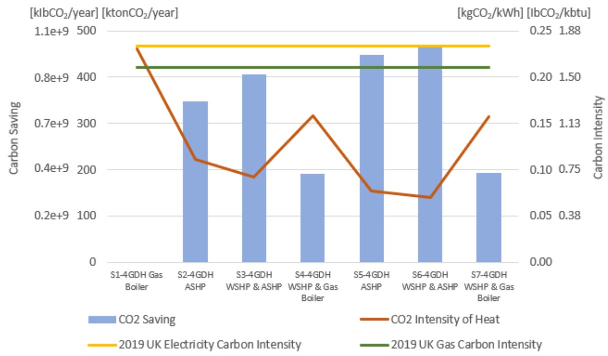

Figure 4. Environmental Scenario Results

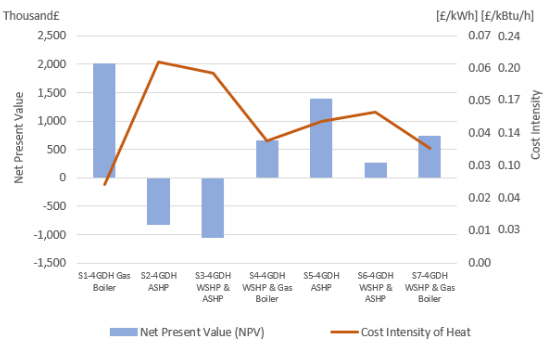

Figure 5. Financial Scenario Results

As shown in Figure 4, scenario S6 provides the greatest carbon emission savings of 468 thousandtonnesCO_2/year [1.03e+9 IbCO_2/year], equivalent to a 70% reduction from a gas boiler only base case. The most techno-economically favourably scenario S7 provides a 29% saving in carbon emissions. From a social prospective, the energy recovery concept helps to enable effective use of heat pump technology that in turn allows district heating operators to provide cost-effective heating when compared to a counterfactual base case. Additionally, the reduction in fossil fuel combustion for heat generation improves air quality in the local area.

Benefits to the Transformer

It can be seen from Figure 6 that the operation of Transformer T1 permits on average maximum hot spot temperatures ranging for 82 to 100°C [180 to 212°F] and on average is electrically loaded to around 40% of its rated capacity, which is shown from the achieved hot spot temperatures with no energy recovery. As cities further develop, electrical loading density increases, that is applying augmented pressure on infrastructure. The process of recovering energy from transformers in turn enhances the cooling mechanism reducing thermal overload, which allows the short term emergency overload to increase without exceeding the maximum permissible limits, resulting in an increased power output available from the transformer. Furthermore, by recovering losses from transformers the efficiency of the transformer and electrical transmission network increases. This can be determined by the reduction in temperature of the transformer core which in turn reduces the resistance through the windings, enabling an electrical power saving. From the modelling carried out, it is estimated that the asset owner of the transformer has the opportunity to generate a revenue of £18,000/year (based on 0.02 £/kWh [0.06 £/kBtu]) from the sale of heat to a district heating operator. The recovery quantity is affected by the electrical loading on the transformer, along with the rated capacity, and the agreed sale tariff.

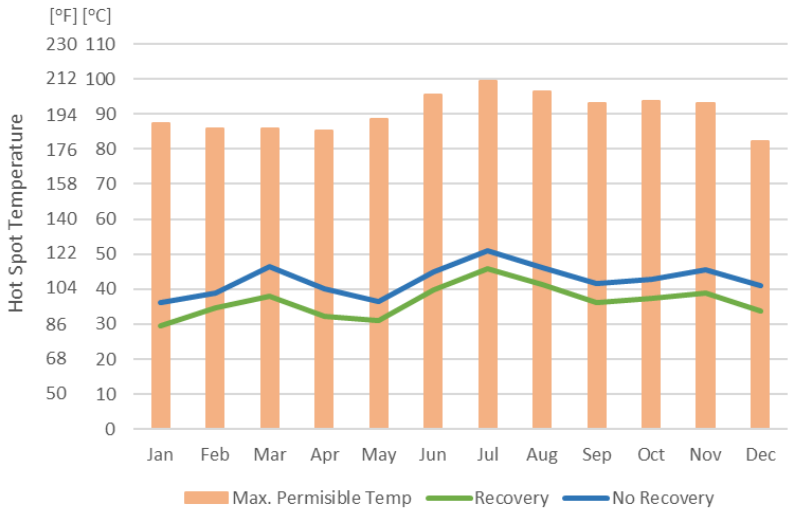

Figure 6. Maximum Permissible Transformer Temperatures With and Without Energy Recovery

CONCLUSION

Losses that occur from electrical power transformers at rated capacities greater than 25MVA provide substantial quantities of heat and at favourable temperatures that can be recycled and used towards the thermal demands of buildings. From the annual modelling results of this study it shows that a heat recovery concept from a 90MVA BSP transformer could contribute to 4.5% of the annual demand of the Southampton City District Heating scheme. Alternatively, 43% of the thermal demand of a low temperature 4GDH network supporting a cluster of buildings could be met. Results show that initial CAPEX is high when the heat recovery concept supports a network with an additional ASHP as a top up heat source to provide the remainder of the demand. However, there is the opportunity to enable the production of heat at a very low CO_2 intensity, contributing to the decarbonisation of the heat sector. Technical benefits occur for the transformer operator, in terms of elevating pressure off electrical infrastructure through the benefits of cooling and providing potential electrical power savings from reduced operating temperatures along with the opportunity to generate revenue from the sale of recovered heat.

ACKNOWLEDGEMENTS

The main author would like to thank North West Electricity for sharing their interest in the study along with providing the substation annual loading profile and for the continued support from the staff at London South Bank University.

NOMENCLATURE

Cp_o	Specific heat capacity oil
Cp_w	Specific heat capacity water
h_2'	Enthalpy considering isentropic efficiency
h_3	Enthalpy after condenser
K	Ratio of loading to capacity
K_{11}	Coefficient factor
$\dot{m}_o$	Mass volume flow rate oil
$\dot{m}_r$	Mass volume flow rate refrigerant
$\dot{m}_w$	Mass volume flow rate water
P_l	Winding losses under an operational load
P_{lr}	Winding losses at rated current
P_t	Total no-load and load losses under an operational load
Q_h	Heating power output
R	Ratio of rated no load losses to load losses
W_{in}	Work done by compressor
x	Liquid exponent
θ_a	Ambient temperature
θ_{of}	Oil flow temperature
θ_{oid}	Previous dynamic step transformer top liquid temperature
θ_{od}	Dynamic transformer top liquid temperature
θ_{or}	Oil return temperature
θ_{os}	Steady state transformer top liquid temperature
θ_{wf}	Water flow temperature
θ_{wr}	Water return temperature
τ	Time step in minutes
τ_o	Time constant

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