SHEFFIELD'S LOW CARBON HEAT NETWORK AND ITS ENERGY STORAGE POTENTIAL

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Confidentiality

The information provided by Sheffield Forgemasters International Ltd and the University of Sheffield Estates Department for the purpose of this study is to be handled in confidence. This thesis has been produced to detail the studies undertaken by Rob Raine under the supervision of Professor Vida Sharifi and Professor Jim Swithenbank, for the purpose of examination in the Department of Chemical and Biological Engineering at the University of Sheffield. Photographs taken on visits to the Sheffield Forgemasters International Ltd. Site and site plans included in this thesis are not to be reproduced without permission from Sheffield Forgemasters International Ltd.

Summary

This research investigates the potential for integration of heat storage into district heating networks, focusing on three varied case studies in the city of Sheffield. Each case study has implications for the future development of district heating and heat storage.

The first case study concerned the potential for heat storage operating alongside proposed CHP units at the University of Sheffield. Heat demand data from the university was analysed to understand variations due to occupancy, weather conditions and other factors. Scenario modelling using Visual Basic algorithms simulated the operation of a new gas-fired CHP installation. Using heat storage was demonstrated to enhance the commercial and carbon benefits for the university from the CHP.

The second case study involved working with Sheffield Forgemasters to assess potential for waste heat recovery and supply to an emerging district heating scheme. Site visits and dialogue allowed for estimation of the quantity, intermittency and temperature of waste heat resources. A novel computer programme was developed to simulate the effects of various parameters on the viability of heat storage with results highlighting a role to manage the production of waste heat as well as wider benefits for the CHP plant and the heat network.

The third case study considered the operation of a city-wide heat network where established and emerging heat networks were interconnected. The running priority for the two CHP plants was optimised by an algorithm selecting heat production from the source of minimum cost. The environmental and economic impacts of interconnection and the addition of heat storage were evaluated.

Overall, this thesis improves understanding of the role of heat storage as the importance of both energy storage and heat networks are growing. This work has benefitted from collaboration with private and public sectors, providing valuable information for policy makers and for identifying future research directions.

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Nomenclature

A	Area/ Area through which conduction occurs (m^2)
a	Annum
AD	Annual demand
c	Specific heat capacity (MWh/kg.K)
C_p	Heat capacity at constant pressure
CoP	Coefficient of performance
CR(t)	Rate of heat addition to the store (MW)
d	Outer pipe diameter/inner insulaton diameter (m)
D	Insulation outer diameter (m)
E/E(t)	Energy stored (MWh)
E_{max}	Thermal store capacity (MWh)
g	Acceleration due to gravity
HL(t)	Heat loss from the store (MW)
HL_0/HL_c	Heat loss coefficients per unit energy store capacity/unit energy stored (MW/MWh)
k	An index referring to the time period, falling in the range 1-48.
k	Thermal conductivity
K	Total heat transfer coefficient with respect to outer pipe surface (W/m^2K)
L	A characteristic length
LIWH(t)	Industrial waste heat lost from the system (MW)
Q(t)	Heat demand as a function of time
$Q_i(t)$	Heat demand under scenario *i*
p	Pressure
P	Electrical power output (MW)
P_{eo}	Electrical output while producing electricity only (MW)
Q	Heat flow over a small distance by conduction (W)
Q_{CHP}	Thermal output from CHP to DH, subscript '*min/max'* for minimum/maximum outputs (MW)
Q_{DH}	Heat supplied to DH (MW)
Q_G	Thermal output from gas boilers (MW)
Q_{IWH}	Industrial waste heat production rate (MW)
Q_L	Heat losses (kW)
r_{xy}	Sample correlation
Re	Reynold's number
Ri	Richardson's number
S	Entropy
$SDE_{min/max}$	Lower/upper bound on the amount of energy stored at the end of the day (MWh)
T	Temperature
t	Time

U	Internal energy
V	Volume (m^3)
V_{xy}	Sample covariance
v	Fluid velocity
W(t)	Power station work output as a function of time
Z	Z-ratio for CHP unit
β	Thermal expansion coefficient
dT/dx	Local temperature gradient (°C/m)
ΔH	Enthalpy change (kJ/mol)
ΔT	Temperature change (°C)
Δt	Step in time (h)
λ	Thermal conductivity of the medium (W/mK)
λ_i	Thermal conductivity of the insulation (W/mK)
ρ	Density (kg/m^3)

Abbreviations

BEIS = Department for Business, Energy and Industrial Strategy
CCA = Climate Change Agreement
CCL = Climate Change Levy
CfD = Contracts for Difference
CHP = Combined heat and power
CHPQA = Combined Heat and Power Quality Assurance
CoP = Coefficient of performance
DECC = Department of Energy and Climate Change
DH = District heating
DN = Nominal diameter
EAF = Electric arc furnace
ELF = Electrical load follow
eq. = equivalent
ERF = Energy Recovery Facility,
ETS = Emissions Trading Scheme
EU = European Union
GWh = Gigawatt-hours (10^9 watt-hours)
HLF = Heat load follow
HTF = Heat transfer fluid
LHD = Linear heat density
MEF = Marginal Emissions Factor
MW = megawatts, subscript ‘th’ for thermal power flows and subscript ‘e’ is for electrical power.
MWh = Megawatt-hours (10^6 watt-hours)
NFFO = Non-Fossil Fuel Obligation
NHPC = Net Heat Production Cost
PCM = Phase change material
QI = Quality Index
QPO = Qualifying Power Output
RHI = Renewable Heat Incentive
ROC = Renewable Obligation Certificate
SFIL = Sheffield Forgemasters International Ltd
TES = Thermal energy storage
TWh = Terawatt-hours (10^{12} watt-hours)
tls = tonne of liquid steel
UN = University of Sheffield network
UoS = University of Sheffield
VAD = Vacuum arc degassing

1. INTRODUCTION

The UK has an ageing energy infrastructure where many large power stations are due to close as a result of various factors including the EU Large Combustion Plant Directive, unfavourable economics for gas-fired plants, and nuclear plants approaching the end of their operational lives. UK energy policy-makers speak of the “energy trilemma” regarding priorities where energy policy needs to balance the affordability, sustainability and security of our energy supply. The UK market for heating is dominated by the use of natural gas as a result of gas infrastructure roll-out during the 20th century. However, now that fuel supplies from the North Sea are falling and there is pressing need to reduce carbon emissions, finding alternative means of providing heat is a priority. This thesis investigates how heat storage could assist in transforming the provision of heating, particularly in cities, to lower-cost and less-polluting solutions.

1.1 Background

The single biggest end use of energy in the UK is to provide heating representing 46% of end use followed by transport then electricity generation (DECC, 2012a). More efficient provision of heat resources can therefore assist the UK economically, environmentally, and in terms of energy security.

Industrial activity and electricity generation usually result in the large amounts of waste heat being emitted to the environment. Electricity generation sites in the UK tend to be large facilities built away from centres of population and there is rarely enough nearby heat demand to make the use of this wasted heat energy. However, connecting power stations to district heating (DH) systems, as happens in Sheffield, can provide many consumers with low-cost heat and significantly displace carbon emissions.

The domestic demand for heat fluctuates significantly according to the time of day, the season, and other factors. Combined Heat and Power (CHP) stations supplying DH networks have to adjust heat output according to the levels of heat demand. If heat storage were implemented, such power plants could instead balance intermittent renewable electricity or demand variations on the national electricity grid. Heat storage can improve DH operation in additional ways, such as reducing the need for supplementary boilers to meet peak heat demands.

DH is a means to supply low carbon and waste heat to buildings, usually as hot water through well-insulated pipes. This section introduces energy demand variation, DH technologies, and the heat storage technologies. The latest research on DH and heat storage will be explored in detail in the Literature Review.

1.1.1 Energy demand variation

Throughout the day the levels of electricity and heat use vary significantly. Electricity is quite difficult to store, so the fluctuations in electricity demand are largely met by switching power stations on or off, or by altering their output levels.

Demand for Electricity

In the UK, the National Grid coordinates electricity generators to meet electricity demand, an example of this variation of the generation mix at a five-minute resolution during a week is shown in Figure 1-1. Notice how nuclear power stations make a near-consistent contribution while combined cycle gas turbines (CCGTs) account for most of the variation in electrical generation.

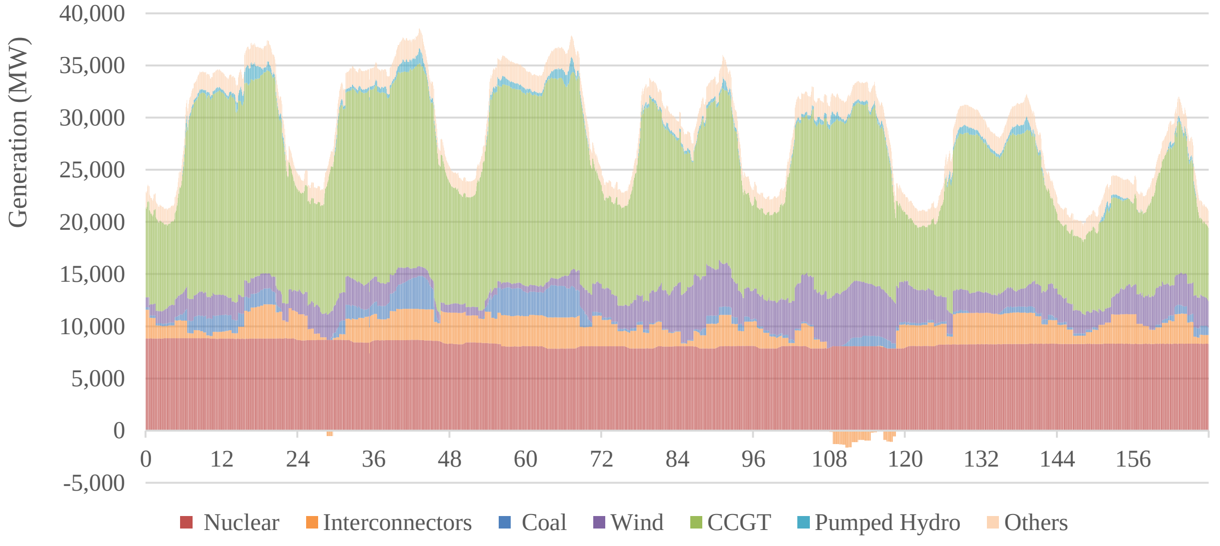

Figure 1-1: Variation of UK electricity generation by fuel type for Monday 5th to Sunday 11th September 2016. Source: Data from GridWatch (2016).

In the UK the amount of wind power is small, reaching around 15% of the national electricity mix at peak times, but this proportion is growing. In Denmark, the output from wind turbines can exceed the national electricity demand and the widespread use of CHP stations with DH and heat storage allows some flexibility to achieve higher electricity prices in the spot market.

Demand for Heating

Heat demand makes up only a small part of the variation in electricity demand since heat demand in the UK is met mainly using natural gas boilers. Figure 1-2 shows how the power supplied through the gas grid compares with the power supplied by the electricity grid; the power delivered by gas is much more variable, and has a much larger peak power value than is the case for electricity.

The gas network manages demand variation through a combination of storage facilities and using the gas pipelines themselves to store gas by raising the pressure for a short period. The fact that renewable heat supplies are generally not as easy to store as natural gas suggests that energy storage ought to have a significant role to play in the UK if low carbon and renewable heat supplies are to be effectively deployed.

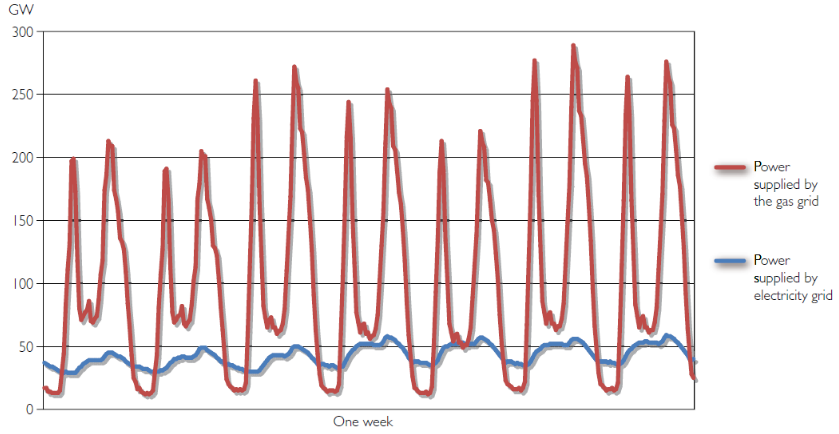

Figure 1-2: The power supplied during a week in winter through the gas and electricity networks. Source: DECC (2012a).

The peak demands for the Yorkshire gas distribution system are actually greater than the rate at which gas can be drawn from the National Transmission System. The local distribution system is used as storage by raising pressure in the pipes; Northern Power Grid used to use local low pressure vessels for gas storage but not any longer (Northern Power Grid, 2013).

1.1.2 District heating

District heating (DH) systems can carry heat from various heat sources, such as power stations or industry sites, to sites of heat demand. Normally, well-insulated pipes are used to carry this heat as hot water or in some cases as steam for high temperature heat demands. In future a greater proportion of heat could be supplied through heat networks using heat sources with lower carbon emissions and that are renewable. Experience of heat networks in the UK is very low, with heat networks meeting only around 2% of building heat demands (DECC, 2013i), but many local authorities are developing strategies to better provide heat to their areas and now is a critical time to consider the potential for various heat sources.

DH systems may prove useful for linking distributed low carbon heat sources, such as solar thermal, to central storage sites which can be large and store heat between seasons. Once in place, the DH system can provide heat from various, and changing, sources without having to alter the technology in the consumer’s property. Work by Poyry Energy Consulting (2009) suggests that it may be economical to develop up to 68 heat networks in the UK serving approximately 8 million UK dwellings.

1.1.3 Heat storage

The importance of innovation and research in heat storage for the UK has been highlighted by the Energy Research Partnership (ERP, 2011) and Low Carbon Innovation Coordination Group in its heat report which mentions the potential benefit for large stores linked to DH networks in order to manage the highly variable demand for heat (LCICG, 2012).

When choosing a store technology, consideration must be given to: the rate at which heat can be transferred into and from the material; how long and how well the heat is retained; the temperatures at which the heat transfer can take place; associated physical changes such as expansion; the economics of the storage technology; and any environmental impacts. A brief overview of heat storage technologies is given here; with much more technical detail in Chapter 2.

Sensible heat storage

All materials contain thermal energy corresponding to molecular motions. Raising the temperature of a material increases the degree of motion of molecules and the amount of energy stored. If the material does not change phase (from solid to liquid or liquid to gas) then this energy storage is called ‘sensible’ heat storage.

Hot water tanks are the most popular option; for example, Figure 1-3 shows two hot water tanks at the interface between Copenhagen’s CHP plant and its DH network. Heat can also be passed to specialist storage materials with high heat capacities, such as regenerator materials used in heat-intensive industry. At high temperatures then solid ceramic materials or thermal oil may be more appropriate than water.

Figure 1-3: Two 22,000m^3 hot water stores at a CHP plant linked to district heating in Copenhagen. Source: DONG Energy (n.d.).

Phase change heat storage

When a material changes from one state to another, for example from solid to liquid, the molecular orderings change and heat can be transferred without significantly changing the material’s temperature. The full amount of heat needed during this change is referred to as the ‘latent heat’. When choosing materials, it is important to find a transition for which heat can be absorbed and extracted at a useful temperature. Cryogenic energy storage offers a phase change of materials at very low temperatures, energy is absorbed in the cooling, and the expansion of gases can be used to drive a turbine.

Chemical heat storage

Chemical reactions alter molecular configurations, and these configurations will have different internal energies. Hence heat can be absorbed in some reactions (termed endothermic) and released in others (exothermic). Reactions can be reversible, where a change in conditions leads the products to become reactants and the reactants to become products; then the reaction runs in reverse and the direction of heat transfer, be it into or from the reaction mixture, changes too.

1.2 Objectives of research

The primary aim of this research is to develop a model to determine how heat storage can be integrated at power stations or industrial sites to facilitate the provision of low cost heat through heat networks and the reduction of carbon dioxide emissions. Objectives for the models are further detailed in Section 3.7. Case studies specific to Sheffield will be investigated since the city's existing and emerging district heating (DH) systems give opportunity for heat storage to improve energy supply to many customers.

The University of Sheffield itself is a large customer on the DH system and is interested in introducing its own combined heat and power (CHP) generation. Work with the University has been undertaken to establish how introduction of CHP and heat storage can help the University reach its own objectives for carbon emissions reductions and form the basis of Chapter 4.

Work with Sheffield Forgemasters International Ltd (SFIL) has investigated means by which they can economically meet targets for their own carbon emission reductions and cost savings, either through the re-use of their own heat or by directing waste heat to DH. This case study forms the basis of Chapter 5.

A close engagement with Sheffield City Council was established to identify how heat storage and other modifications to the city's decentralised energy system can assist in achieving the city's vision for objectives such as reducing fuel poverty and acting as a low-carbon 'beacon' city. This work considers how heat storage could complement existing parts of, and possible future extensions to, the city's heat network. This case study forms the basis of Chapter 6.

1.3 Layout of thesis

This thesis proceeds with a Literature Review into the technologies used for heat storage, looking at developments in research as well as the technologies deployed in industry. The review investigates the modelling techniques applied to assess the technologies and identifies the limits of knowledge.

The Theory chapter lays the basis for studying heat production, distribution and storage. This chapter explores aspects of thermodynamics, economics and environmental impacts relating to the use of heat.

Three chapters then detail the case studies, investigating important features of how heat is produced, distributed and consumed in the city of Sheffield. Each case study investigates options for heat storage, each with their own economic and environmental analyses for introducing new technology.

These case studies are:

i) The University of Sheffield campus;
ii) Sheffield Forgemasters International Limited;
iii) Sheffield's District Heating Networks.

A Discussion chapter follows to evaluate and discuss the significance of the findings. The Conclusions chapter presents the overall findings in context.

2 LITERATURE REVIEW

Existing heat stores are predominantly hot water stores, both at domestic level and in district heating (DH) applications. Water has advantages of low cost, high heat capacity and can be both the storage medium and the heat transfer fluid. Many other technologies are possible but few have been commercialised, for various reasons. A review of the storage technologies and the modelling approaches will help identify novel heat storage technologies and applications.

There are a range of potential roles to be played by heat storage, including:

- Enhancing revenues of energy generation through absorbing energy during low price periods and supplying energy at high price periods;
- Providing resilience of energy supply – producing heat if the usual heat source suffers from failure;
- Capturing energy that otherwise would go to waste, for example at energy-intensive industry sites.

Identification of appropriate characteristic needs for each role will determine which are the best storage technologies. Important consideration should be given to:

- The temperatures suitable for heat absorption and release;
- The required rates of charge and discharge;
- The size of heat store needed and limitations on available space;
- The duration of heat storage, and how much heat loss is acceptable over that time;
- Whether the store is designed to be stationary, transportable by bulk, or continuously pumped (for example through district heat networks);
- Costs of different systems;
- Possible social effects such as the loss of public space;
- Environmental impacts.

These specific needs will mostly interact with each other, leading to compromises as well as opportunities for novel technologies to be developed to meet specific needs. The potential applications for heat storage need to be designed with the consideration that excess heat can be produced at a range of temperatures and pressures and can be carried by various heat transfer fluids. These heat sources will be discussed briefly first in order to identify the market in which heat storage can be deployed.

2.1 Heat sources

2.1.1 Power Stations

Heat is a major by-product in most electrical power stations. Figure 2-1 provides an illustration of the UK's 'centralised' power station processes at Drax. The boiler, where biomass is generally replacing coal to generate high-energy steam, is depicted near the centre of the diagram (labelled number 10). To the left is shown the electricity infrastructure supplied from the plant and also the site of waste heat rejection at the cooling tower.

Drax was designed to produce low cost electricity, and this meant the construction of a very large power station close to the coal fields but a long way from the centres of energy demand. By-product heat is simply lost to atmosphere from the cooling towers. The UK currently requires a significant development of new electricity generation capacity and the choice of generation technology could determine its sustainability. The high cooling needs of a possible new generation of nuclear power stations, for example, could have significant impact on the environment in terms of fish impinging and entraining in the cooling system and the increased estuary water temperatures (Environment Agency, 2010).

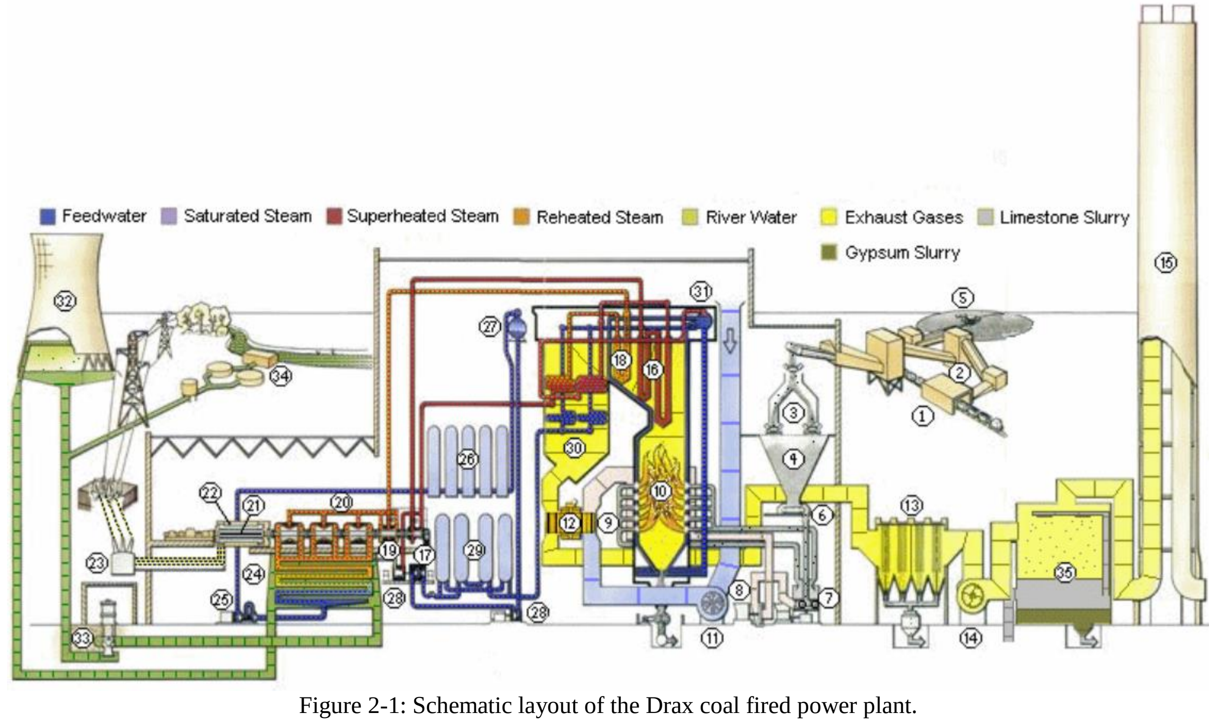

Figure 2-1: Schematic layout of the Drax coal fired power plant.
Source: Drax Group plc (2012).

Combined Heat and Power (CHP) facilities can achieve higher overall efficiencies than electricity-only power stations by distributing heat energy to sites of heat demand but their historic use in the UK has been low. Swithenbank et al. (2012) found that the next generation of power stations could include more Energy from Waste CHP power plants providing a better solution than traditional waste disposal, potentially meeting 15-30% of energy demand for urban areas (*ibid.*).

Sheffield is one of the few UK cities that currently has large-scale use of CHP. A schematic of Sheffield's Energy from Waste CHP plant is shown in Figure 2-2. Combustion gases at 1200°C are cooled to 140°C in the boiler and economiser units where steam is raised to 400°C and 45bar and sent to the steam turbine (Kirkman et al., 2010). After the turbine, the steam is at 42°C and 0.08 bar absolute pressure under design conditions. A bleed on the turbine extracts steam at 145°C (3 bar) and this then feeds two heat exchangers at 141°C (2 bar) from which district heating (DH) water up to 120°C emerges. The water pressure is then raised by pumps to 16 bar for distribution in the DH network (*ibid.*).

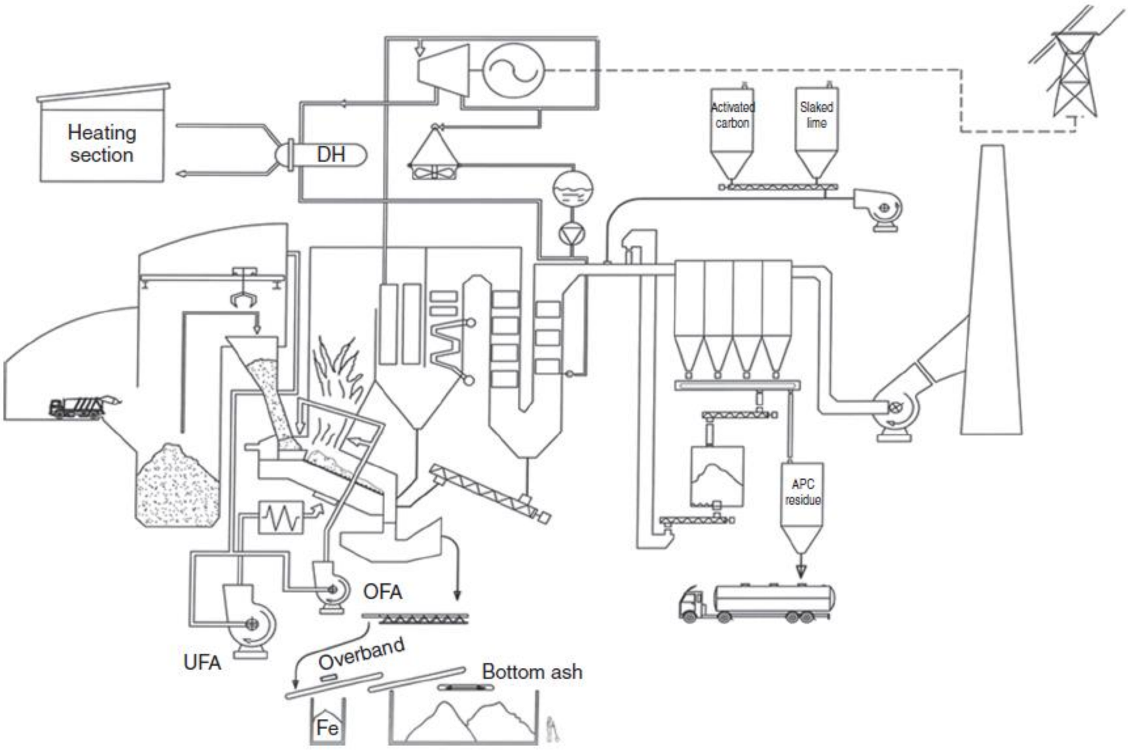

Figure 2-2: Schematic of Sheffield's Energy from Waste CHP plant.
Source: Kirkman et al. (2010). DH = District Heating, OFA/UFA = over/under fire air, APC = Air Pollution Control.

Denmark is a global leader in the use of DH; local authorities there undertook regional planning to define the geography of DH and natural gas networks (Christensen and Jensen-Butler, 1982). By 2007, 61% of Danish homes were connected to DH, and these numerous networks have provided opportunities to facilitate growth of CHP technologies (ENS, 2012). The share of electricity from CHP has grown from 18% in 1980 to 53% by 2010 (*ibid.*). In Odense, Denmark, a 75,000 m^3 thermal storage tank allows the CHP station to switch off overnight and during summer weekends (Ramboll, 2013). The high penetration of wind power in Denmark, in combination with such high levels of CHP and DH has made heat stores an important part of the overall control of the electrical system (IEA, 2005a).

The UK's Low Carbon Innovation and Coordination Group in 2012 identified the use of heat stores with CHP units and associated DH networks as a priority area for research (LCICG, 2012). Optimised use of accumulators in DH systems is estimated to save 5-10% of both carbon emissions and fuel costs (Schneider Electric, 2012).

Solid fuel CHP stations tend to operate with steam turbines as above, however most small scale CHP units are natural gas reciprocating engines generating heat from their cooling water and exhaust. There are a few examples of fuel cell CHPs too, for example Woking Council introduced a fuel cell CHP system in 2003 (Woking Borough Council, 2007) as did One Fenchurch Street in London (Fuel Cell Today, 2012) where tight air quality regulations favour the fuel cell's very low nitrogen oxides (NO_x) emissions. Organic Rankine Cycles are another option, allowing lower operational temperatures than with steam. Natural gas engine CHP units can take 20 to 30 minutes to start up and therefore heat storage assists operation as seen in Pimlico, London (Eames et al., 2014). The Energy Technologies Institute is also investigating the potential for small modular nuclear reactors to provide heat and power for cities (ETI, 2015b).

Many renewable energy sources generate very little heat such as is the case for wind turbines and solar photovoltaics. However, large concentrating solar power plants also generate high temperature steam or thermal oil so there are opportunities there to store thermal energy as well in order to alleviate intermittency of electricity production, some examples are explored in Section 2.4.

2.1.2 Industrial and Commercial Heat Sources

Figure 2-3 shows the levels of heat demand according to temperature across industrial sectors in the EU. Note the large, high temperature demands for iron/steel industries for their furnaces.

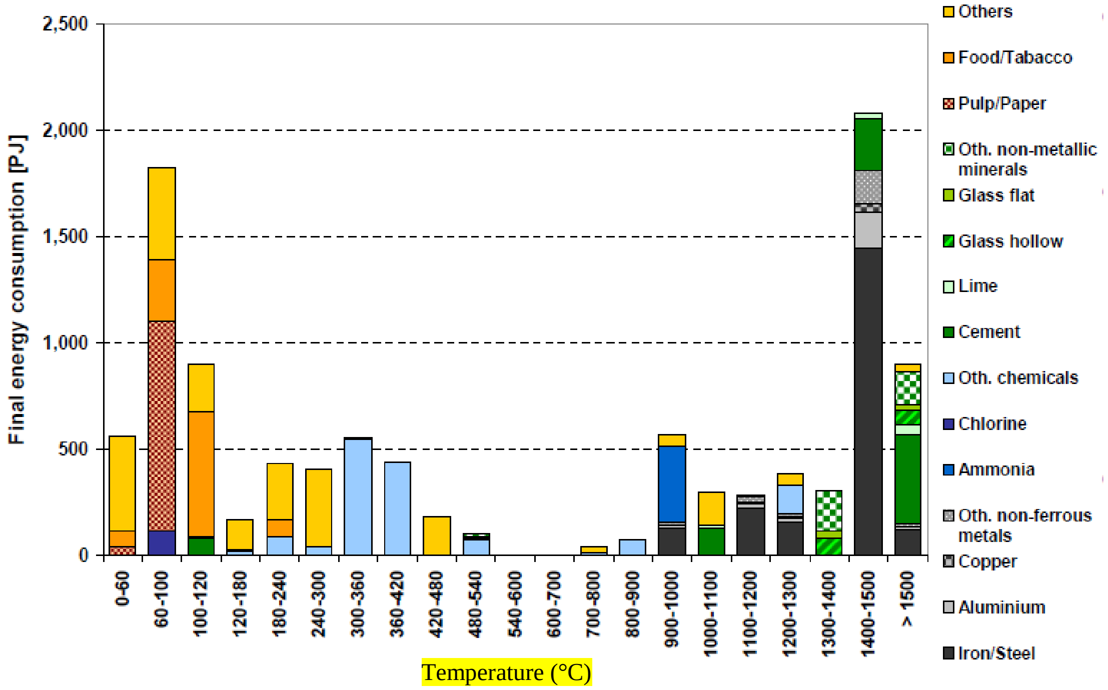

Figure 2-3: Aggregated industrial heat demands by temperature range for the EU-27 countries. Source: Kuder (2010).

There was approximately 185 TWh of demand for heat in UK industry in 2008 (DECC, 2012a), and this demand is compared with other heat demands in Figure 2-4. Electric arc furnaces reach high temperatures necessary to melt steel using electrical heating and this represents a large fraction of the iron and steel sector's carbon footprint; the emissions associated with electricity use in the iron and steel sector added up to 1.95 million tonnes of CO_2(eq.) in 2013 (DECC, 2015b).

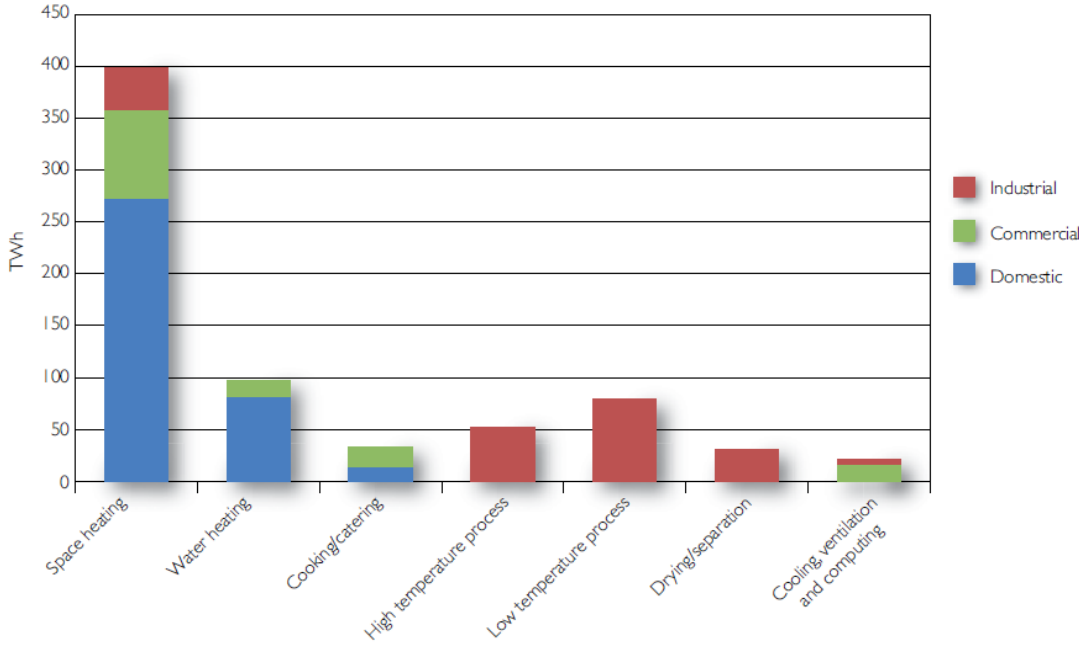

Figure 2-4: Energy consumption for heating by subsector and end-use.
Source: DECC (2013i).

Figure 2-5 shows energy consumption according to industrial sector in the UK. Around 1990, UK electric arc furnaces (EAFs) consumed 4.4 TWh/yr (0.38 mtoe/yr) compared with 87 TWh/yr (7.5 mtoe/yr) for the whole iron and steel sector (Bauer et al., 2004). The amount of energy used by industry in the UK, particularly iron and steel, has been falling but in locations where industry is close to urban areas there may be potential for waste heat recovery.

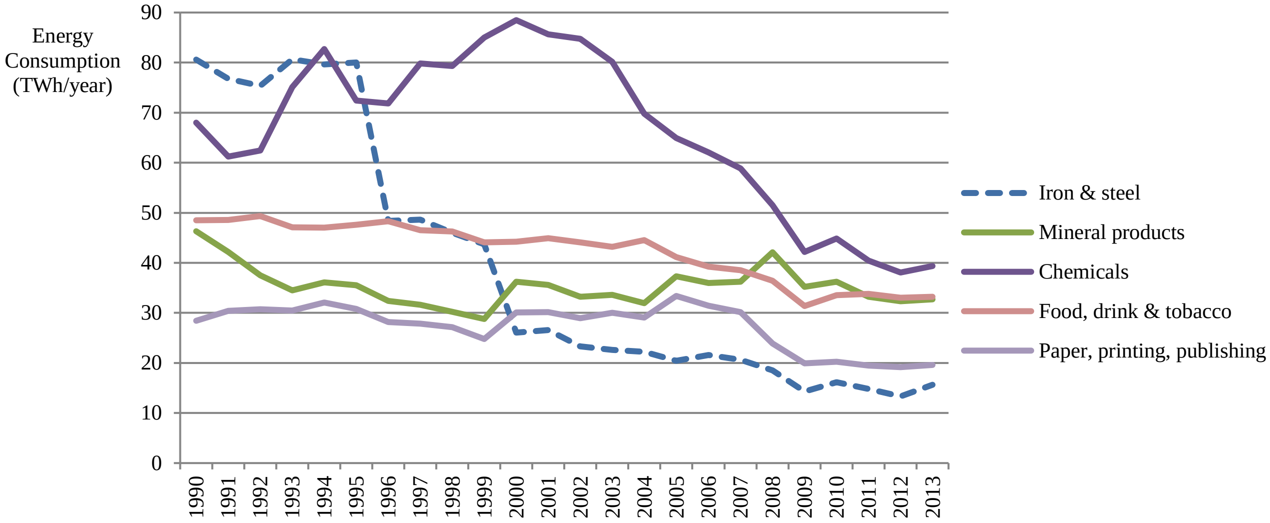

Figure 2-5: Annual energy consumption for some energy-intensive industry sectors.
Note: 5 mtoe= 58 TWh. Source: Adapted from DECC (2014m).

Griffin et al. (2012) reviewed the past programmes for implementing energy efficiency technologies into UK industry, emphasising how partnership between industries and government and academia can work well by providing the authority necessary for investment to occur. The Carbon Trust and InnovateUK (formerly the Technology Strategy Board) is the main mechanism for this interaction now, with incentivised uptake of existing technologies through the Enhanced Capital Allowance scheme (*ibid*.). Industrial Decarbonisation and Energy Efficiency Roadmaps published by the UK government noted that many efficiency measures had already been implemented, and the main carbon footprint reduction in business as usual scenarios was associated with reduction in carbon emission factor for grid electricity (DECC, 2015b). There is also now a requirement under the EU Energy Efficiency Directive to investigate supplying heat to DH when there is construction or refurbishment of large thermal equipment (DEFRA, 2014); some have suggested that this has a perverse effect with industry and power stations siting themselves at a greater distance from demand (Graham, 2013). The UK's Climate Change Levy (CCL) and Climate Change Agreements (CCAs) encourage industry to act on energy use and reduce emissions. Specifically, CCAs for the period 2013-2023 have targets for improving energy efficiency in industry by 2020, with the Steel sector aiming at a 6.8% improvement (DECC, 2013j).

Sweden leads Europe in terms of industrial heat recovered for DH with 10 TWh (36 PJ) produced for DH in 2003 (Werner, 2006). Element Energy (2014) investigated UK potential for industrial heat recovery, but not that from electric arc furnaces; they identified 11 TWh/year as technically recoverable, and 8 TWh/year as economically recoverable. Studies of industrial waste heat potential in the UK (McKenna and Norman, 2010) (McKenna, 2009) assumed low potential at EAF sites due to widespread use of scrap metal preheating, but only one of the UK EAFs (now closed, Kent Online, 2013) did this (Environment Agency, 2004). McKenna and Norman (2010) also neglect exothermic reactions as sources of recoverable heat, but these could be relevant in the case study of Chapter 4.

Sheffield provides an interesting case study for this work with numerous industrial sites for potential heat recovery, including many for steel production. These sites lie primarily in Sheffield's Lower Don Valley, and it is conservatively estimated that ten sites could each provide 1MW of heat (Finney et al., 2012). This heat is unlikely to be produced at the time it is needed, suggesting a role for heat storage. Sheffield's large DH network may provide a good opportunity for the city's industries to become more competitive and environmentally-friendly; demonstration of heat capture in Sheffield may encourage other cities to develop DH to capture industrial heat and incorporate low carbon heat sources. Sheffield Forgemasters has committed to investigating feasibility of using waste process heat from on site in order to supply the new DH in the Lower Don Valley (SFIL, 2012).

Upham and Jones (2012) investigated the public opinions on the use of industrial waste heat for district heating (DH) in Port Talbot, finding that amongst the possible heat sources considered the use of waste process heat was viewed most favourably, but the issue of contractual lock-in for DH was a significant barrier.

In Dunkirk, France, heat recovery from the sinter processing at a primary steelworks supplies the majority of heat to a DH network. The air-cooling of sinter-products provides 28MW of heating capacity in an arrangement shown in Figure 2-6; heat is supplied to the network at 105°C (European Commission, 2013).

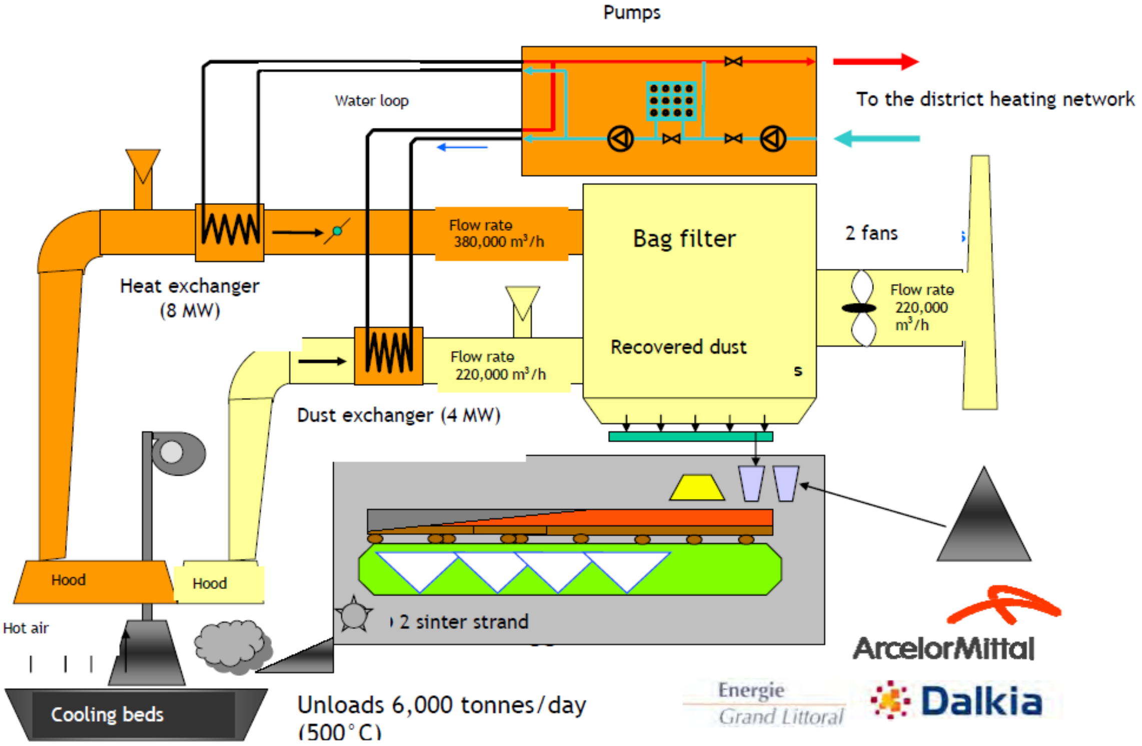

Figure 2-6: Heat recovery at the Dunkirk steel plant for the district heating network.
Source: Dalkia (2009).

In Sweden, 40 GWh/year of waste heat from one site with steel furnaces is delivered to a local DH system, supplying heat to 70% of the town of Oxelosund (ssab.com, 2013). In 2012, each tonne of steel produced, either in a blast furnace or electric arc furnace on site, had a by-product heat of 220kWh sent to DH (SSAB, 2012). In order to sell more heat from the facility further afield, a trial for supply of heat on trucks was carried out with boiling water from a salt; the capacity was 17MWh on each 14 tonne truck (Martin, 2010). The primary difficulty was found to be the need for a low grade heat source to provide moist air at the demand side (*ibid.*).

There are significant examples of success in using industry waste heat for DH in Europe. In Gothenburg, 24% of the energy for DH in 2010 was recovered heat from industry (Göteborg Energi, 2014). Subsidies in Sweden help recover heat including 240 million SEK (£22 million[1]) of funding invested in heat recovery schemes delivering 370 GWh of heat (Ericsson, 2009). Figure 2-7 shows one example from the Ruhr in Germany where 350 GWh of heat per year is recovered representing 58% of the total DH supply (Frederiksen and Werner, 2013). Other European examples of use of waste heat from a steelworks for DH include Raahe in Finland, and Lulea in Sweden (European Commission, 2013).

[1] Exchange rate of 10.75 SEK to 1 GBP in September 2016 (Travelex, 2016).

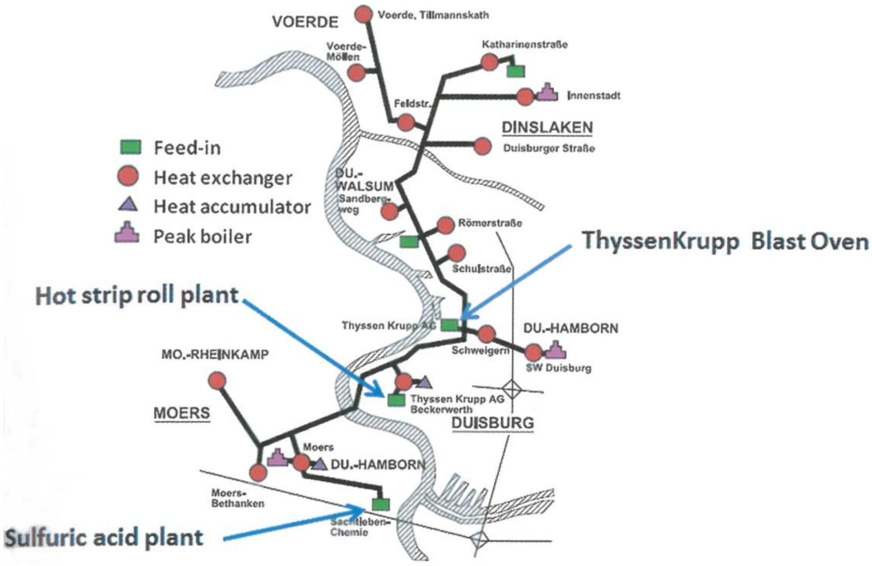

Figure 2-7: Schematic of two steelworks and a chemical plant attached to a district heating network.
Source: Frederiksen and Werner (2013), adapted from Richter and Mandelfeld (2007).

There have also been many studies to investigate the potential for heat recovery. In Japan, heat cascading models where waste heat at one temperature level was passed to a demand at a lower temperature level were demonstrated by Hayakawa et al. (1999). Oh et al. (2014) went further by matching heat from a variable industrial process to variable heat sinks nearby by considering discrete time periods and carrying out pinch analysis in those periods to minimise the need for supplementary heat sources. Gustafsson (2013) analysed the potential for increasing heat recovery for DH in Sweden, finding a high sensitivity to the DH operating temperatures. Fang et al. (2015) describe innovative work with heat networks using heat pumps to achieve low return temperatures of less than 45°C, as well as to achieve effective heat recovery at low temperatures in an optimal manner using a new theoretical technique similar to pinch point analysis. Their work also notes that upcoming work to store the low grade recovered heat underground could increase effectiveness.

Recent work has investigated waste heat recovery from both the London Underground and transformers on the electrical system for use in DH using ammonia heat pumps (Islington Council, 2015); varying the temperature according to time and location on the network could be critical to success with that network operating around 84°C in places (Matson, 2014). Heat pump use in Sweden for heat recovery occurs mainly in the Swedish paper and pulp industry where they recovered approximately 250 GWh in 2007 (Frederiksen and Werner, 2013). The most frequently used heat source in the paper mill is the effluent streams (Gustafsson, 2013). At Ovako Steel in Hofors, Sweden a combination of heat exchangers with heat recovery from EAF flue gases and a heat pump to supply extra heat to DH allow contribution of 19 GWh per year or about 25% of the DH system needs (SFS AB, 2002). A 8,500 m^3 hot water tank was installed in Hofors to manage the different heat sources more effectively (SEPA, 2010).

There are regulatory issues such as the status of third party access; these issues also apply in electricity networks which have a much wider geographical scale. The economic risks, already high, for network investment would be increased if there was third party access that could reduce profitability (SFS AB, 2002). In Sweden, there is a current discussion over whether it should be mandatory for third parties to be able to access DH networks (Gustafsson, 2013). According to Lennermo et al (2014), statutory access in Sweden was denied; however the utility Fortum which operates in Sweden has launched an initiative for organisations to deliver waste heat to DH systems (Fortum, 2015). The Stockholm DH system is now receiving waste heat from a data centre, provided to the network at 68°C (Fortum, 2015b).

An alternative heat recovery opportunity arises if radiated heat on industry sites could be used to power thermo-electric devices which generate electricity, like solar cells do for visible radiation. Thermo-photovoltaic applications were described by Bauer et al. (2004) and their applications remain in the early stages. A European research project (THERELEXPRO) is underway to determine the possible uses of low temperature (less than 350°C) waste heat for thermoelectric electricity generation (European Commission, 2013c).

2.1.3 Heat Pumps and Chillers

Heat pumps are used to produce heat by drawing thermal energy from the ambient and raising its temperature; the process efficiency is generally higher when the temperature gap between ambient and supply temperatures is lower. Heat pumps are expected to have an important role in the UK government plans to reduce carbon emissions from heating particularly in locations where gas grids and heat networks are not feasible (DECC, 2013i). Heat pumps benefit from the use of heat stores to balance supply and demand as well as moving electricity demand away from peak hours but the capacities required are large (Eames et al., 2014); ground loops allow the storage capacity of the ground to be accessed and hot water cylinders allow for short term buffer storage of hot water.

Many households have heating systems with a fossil-fuel boiler, using water at 80-90°C where temperature drops by 10-20°C through the radiators. Commercial heat pumps heat water to 50-60°C and have temperature drops of 5-6°C (Sanner et al., 2003) and hence the radiator systems may need replacing. High temperatures are still necessary for domestic hot water. The use of heat pumps to add heat to DH have been identified as a research priority by the Danish government (ENS, 2011) and German government (BMWi, 2011). Most electrically-driven heat pumps operate through vapour expansion and compression with the temperature of heat supply depending on the pressure at which its condenser operates.

The UK Department of Energy and Climate Change (DECC) has been monitoring early adopters of heat pump technology to assess performance of the heat pumps. Data released in January 2014, show mean performance of 3.01 for ground source heat pumps (GSHPs) and 2.71 for air source heat pumps (ASHPs) in these cases, with 69% of the ASHPs qualifying as producing renewable energy according to EU Renewable Energy Directive and 84% of the GSHPs (DECC, 2014). The emissions factor for UK electricity will be important to determine environmental impact of a heat pump driven by electricity and this will change over time according to the electricity generation mix.

There is a lack of working fluids which can operate at high delivery temperatures since many fluids are banned due to their high ozone-depletion potential or global warming potential. In some cases of heat recovery there is a requirement to top-up the temperature using boilers on site (Gustafsson, 2013). With ammonia as a working fluid, high delivery temperatures are possible but the necessary pressure increases with temperature, as in Figure 2-8, making heat pump design difficult. The latent heat for vapour phase change also diminishes as the condensation temperature rises towards the critical point. Ammonia heat pumps are suitable for heat delivery at up to 105°C, while steam-water working fluid can be used up to 180°C according to Tamura et al. (1997). With water-based heat pumps evaporation occurs below atmospheric pressure and air leaking in needs purging from the fluid to maintain performance (Chamoun et al., 2012).

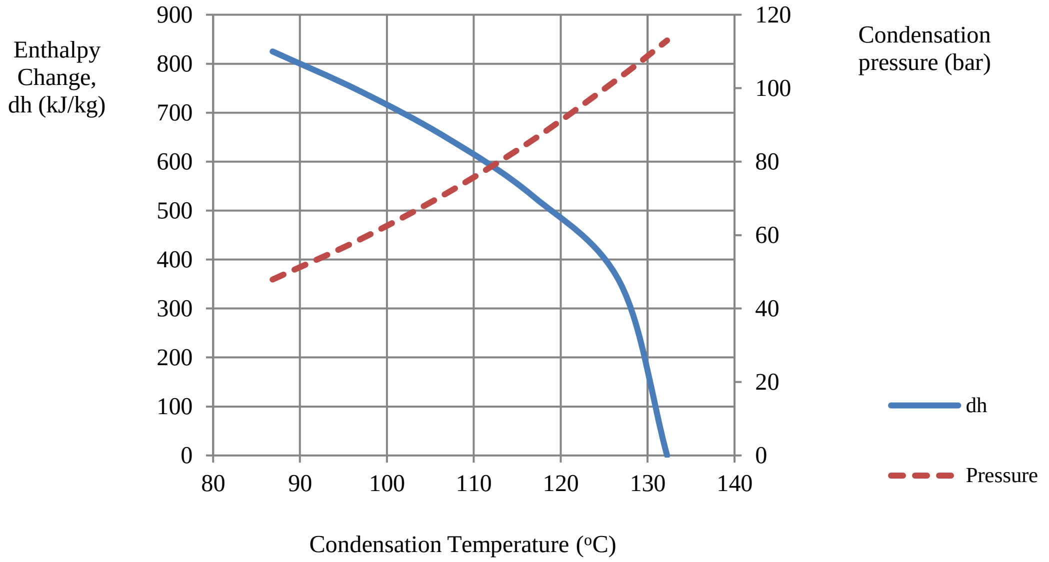

Figure 2-8: Enthalpy change and pressure of condensation for ammonia at different condensation temperatures. Source: Data from Perry and Green (1997).

Absorption heat pumps can be used to supply heat in winter and cooling in summer, or could supply both simultaneously (Frederiksen and Werner, 2013). Absorption chillers, like that shown in Figure 2-9, use heat energy to drive a cycle that delivers cooler-than-ambient water; such technologies are being applied in research for applications such as solar-powered cooling systems in Spain (Oro et al, 2012). These chillers can also use the heat from DH systems or waste heat sources to provide cooling.

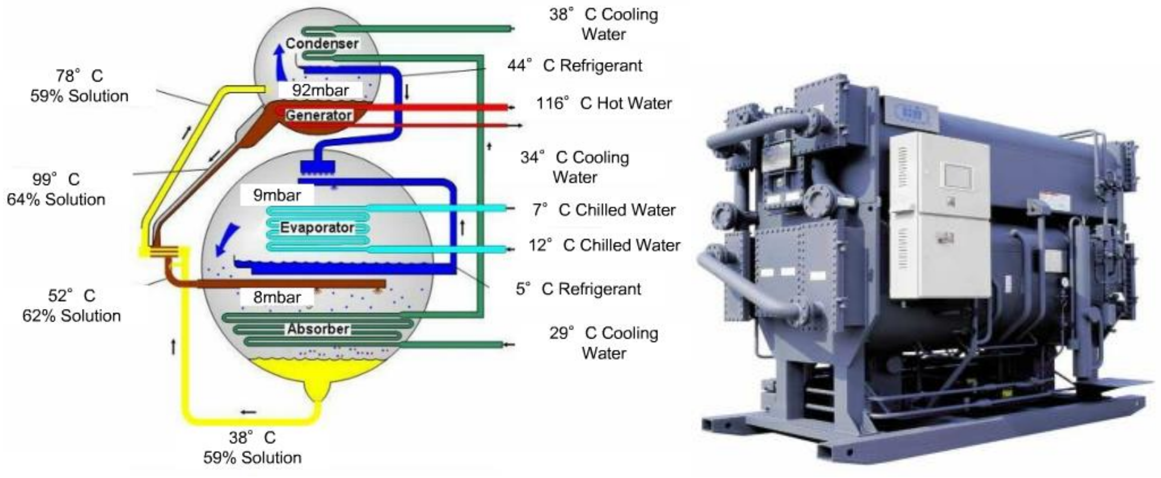

Figure 2-9: Absorption chiller function schematic (left) and the external appearance (right).
Source: Clarke Energy (2013).

Single-effect absorption chillers require low pressure steam and achieve a coefficient of performance (CoP, explained in Section 3.1.5) of around 0.7, while double effect absorption chillers require higher temperature and pressure steam but achieve better CoP of around 1.0 (DoE EERE, 2012b). Desiccant chillers are an option that may be worth further investigation, however these technologies are not widely implemented yet. Absorption chilling reactions using Lithium Bromide (LiBr) and water cannot work below 0°C, but this temperature is feasible with a water/ammonia system. Cold storage is viewed as near-essential for cooling networks as the demand is by nature very intermittent (Frederiksen and Werner, 2013). The use of diurnal cool storage in the United States is estimated to have shifted 15 GW of cooling power to off-peak periods (Dincer and Rosen, 2002).

Basciotti and Pol (2011) point out that these absorption chiller systems usually return the district heating water with a small temperature drop, which can be problematic for maintaining efficiency of the CHP power plant; they suggest instead the use of desiccant cooling systems that result in a larger temperature drop.

Heat pump experience

An ammonia heat pump producing water at 90°C has been implemented in the Norwegian town of Drammen as a prototype recently and has achieved a coefficient of performance greater than 3.0 over the winter months (Helskog, 2012). The sea water heat source is only around 8-10°C (Helskog, 2012). The heat pump operates as follows (BBC, 2015):

1. Water from the fjord heats liquid ammonia at 4 bar pressure until it boils at 2°C,;
2. Pressure is raised to 50 bar heating the gas to 120°C;
3. The hot gas then is used to heat the DH water from 60°C to 90°C.

In Borlänge, Sweden three heat pumps deliver 71% of the demand of a large DH system (Gebremedhin, 2003). A particularly effective option, exploited in Stockholm, is to use a heat pump to deliver cooling to a cooling network and heat to a heating network at the same location.

2.1.4 Other Heat Sources

Solar thermal energy is an improving technology which achieves better economics if the heat can be absorbed in summer and stored until there is greater need for heating in winter. It is estimated for houses in Scotland that solar gain already provides 15% of the space heating need (University of Strathclyde, 2002). There are many examples from Europe where large hot water stores have been used to store solar energy for DH. One of the main advantages of a heat network is that you can have multiple suppliers of heat which can vary their input according to which is most economical.

Geothermal resources are less well studied. According to data shown in Figure 2-10, Sheffield would have geothermal potential of around 65 mW/m^2 whereas projects in Cornwall are looking to take advantage of values over 120 mW/m^2 (theEngineer.co.uk, 2011). The heat flows around Sheffield seem to be moderate by national standards; however, the existence of a DH system in Sheffield may mean a better case trying this technology.

Newcastle and Manchester have research efforts into their geothermal potential linked to DH possibilities (DECC, 2012e). The surface footprint for geothermal heat supply is small and this means that the heat generation can be inserted close to the city centre, as is in the advanced planning stages for Manchester (GT Energy, 2013). Newcastle University is part of a scheme that, since 2011, has been testing the geothermal aquifer water (NIReS, 2012). In Southampton, drilling to a depth of 1.7km has been undertaken to extract heat from geothermal sources (Southampton City Council, 2011).

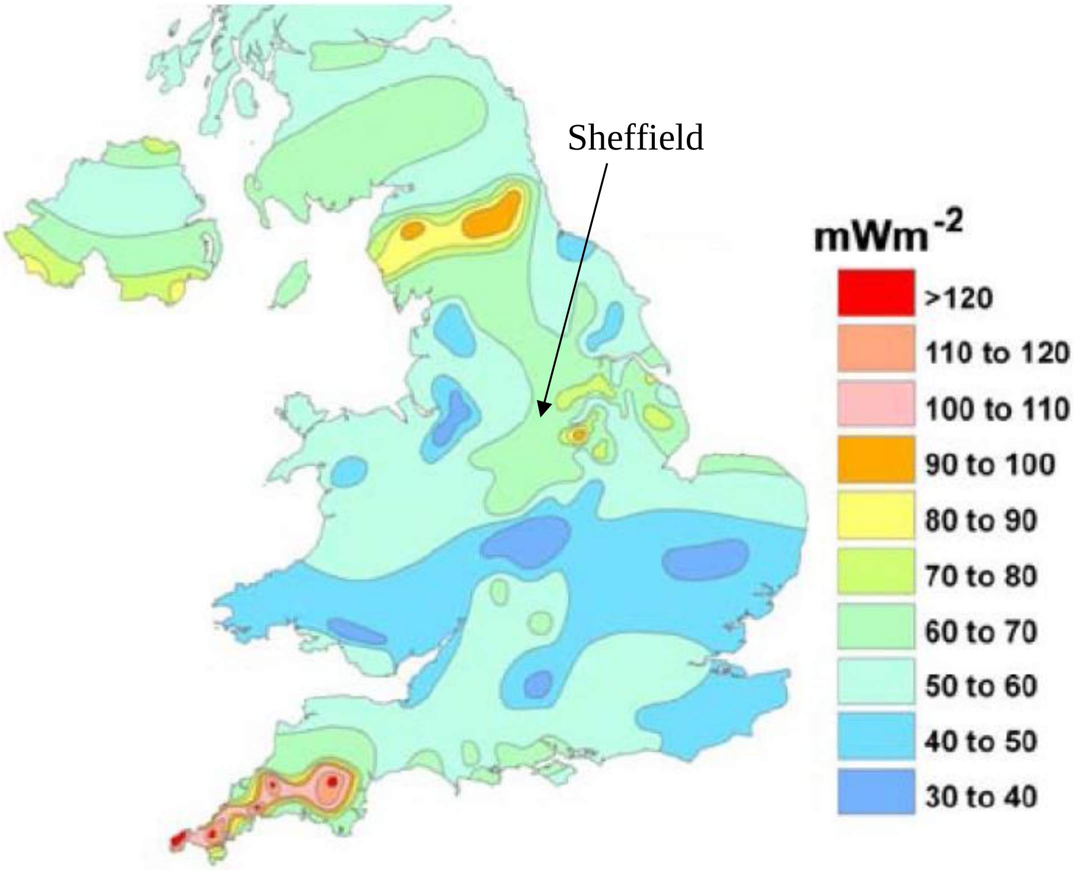

Figure 2-10: Geothermal heat-flows in the UK.
Source: Busby (2011).

Increasingly, data centres are also emerging as producers of large amounts of heat; for example in Espoo, Finland, a large data centre which provides enough heat to heat 1500 homes (30GWh per year) is going to be connected to supply DH (COSPP, 2013) as is the case in Stockholm where the DH utility absorbs various waste heat sources (Fortum, 2015).

Currently electrical energy is stored mainly through pumped storage, but around 30% of the energy is lost when pumping the water up hill and 20% is lost during the discharge process (Dincer and Rosen, 2002). Compressed air energy storage involves rejection of a large amount of heat during compression so storing this heat and resupplying heat during expansion may provide a role for heat storage (Dincer and Rosen, 2002). Such systems are being investigated (e.g. Bullough et al., 2004), but compressed air energy storage applications are limited by the need to access large gas store facilities and needing a dedicated gas turbine through which to expand.

2.2 Heat Storage General Principles

There are three main categories of thermal storage: sensible stores that charge and discharge through changes of temperature but not change of phase, phase change materials that charge and discharge through heat absorption and emission during changes of phase and thermochemical storage where a chemical reaction absorbs or emits heat.

Investigating practical issues for various heat storage applications will help identify which technologies will be appropriate. A description of the policy setting in which the technologies would operate, this is important for the understanding of whether a technology will be successful and can be widely applied.

Some storage technologies constitute holding the heat transfer medium itself (usually accumulators of hot water or steam), others require conduction of heat across contact surfaces such as pebble bed ceramic regenerators, while others rely on conduction through heat exchangers which separate heat transfer and storage media such as with ground source heat pumps.

The choice of store technology needs to consider technical and economic matters as well as environmental and social factors. As an example of a social factor, a heat store installation may reduce the amount or quality of open space available to the local community and affect the visual appearance of the area (Eames et al, 2014).

Materials undergoing phase change gives the opportunity for a large absorption of heat energy over a small temperature range, meaning that a lower quantity of material is required to store the energy. Also the release of heat at near-constant temperature is useful in some applications.

Chemical reactions also have the potential to absorb energy, but the separation of products to prevent premature recombination could help to conserve it. However, the practical experience of using these systems is low.

There are two main reversible ways in which chemicals can be deployed for energy storage:

- Thermochemistry – where heat is absorbed or given off as a reaction takes place;
- Absorption and adsorption – energy changes associated with a fluid coming into contact with, and being liberated from, a solid.

In both cases, it is important to select reactions which are suitable for cycling since the absorption and release of heat should be repeatable. Reactions leading to degradation of the material should be avoided and this includes that the molecules need to show stability over many cycles at the temperatures at which heat transfer takes place.

2.2.1 Heat Transfer Fluids

Water in liquid or steam form is most often used as a heat transfer fluid (HTF) since it is low cost and has a high heat capacity. The boiling point of water can be raised by using higher pressures, see Figure 2-11, making it feasible to use liquid water significantly above 100°C. DH systems commonly work with supply water temperatures at 80°C or 120°C. For heat transfers nearer 200°C the use of steam or thermal oils is usually more practical.

Storing the HTF itself carries an advantage in that the necessary temperature drops for heat to transfer to another material and back again can be avoided, thus the heat remains at a higher temperature.

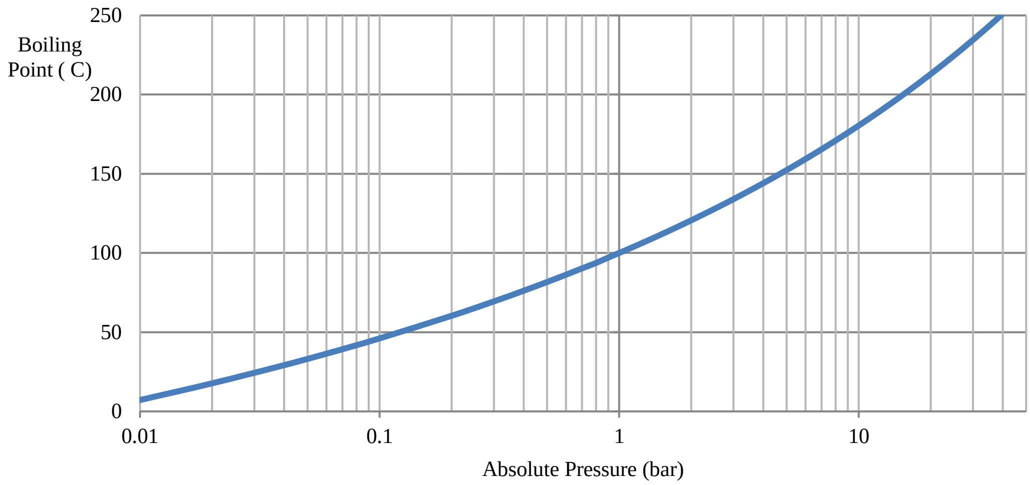

Figure 2-11: Variation of the boiling point of water with pressure.
Source: Data from CIBSE (2007).

For DH networks, the HTF temperature is very important due to its effect on heat losses and the efficiency of heat production. Experience has shown that the instantaneous production of hot water can help keep network operating temperatures lower; this is because when a hot water cylinder is present in the property there is a need for a high temperature source to avoid *Legionella* risks. The hot water for hygiene purposes perhaps only needs to be 45 or 50 °C at the point of delivery hence allowing lower temperatures for instantaneous hot water systems (Matson, 2014).

2.2.2 Modelling Phase Changes

The behaviour of phase change materials during charging and discharge is complex and much theoretical work has been undertaken to understand these phenomena.

Morrison and Abdel-Khalik (1978) developed models of the transient behaviour in PCMs (sodium sulphate decahydrate and paraffin wax) using energy balance differential equations. A simplified version of the equations was shown by Hughes et al. (1976) to be a good model for rock beds where the NTU coefficient is near-infinite (approximating to low thermal conductivity of the heat transfer fluid).

Carlsson and Wettermark (1980) look for mathematical relations using experimental results for heat transfer changes in PCMs while they are changing phase. Lecomte and Mayer (1985) used thermal models for the growth of the front of fusion around heat exchanger pipes in order to establish optimal dimensions for the heat store.

Lacroix (1993) followed this work with a numerical model that showed the advantage of using fin structures. The model was validated by experimental data. Similar modelling by Esen et al. (1998) showed that appropriate geometries for PCM stores vary depending upon the PCM material to be used so there is no one size fits all, but they work out some scales appropriate to specific materials. Models are based on cylinders of PCM surrounded by heat transfer fluid and vice versa. Their model is applied to a real system in (Esen, 2000) in order to make suggestions how to improve performance.

Stritih (2004) uses models for heat transfer and fluid flows to look at heat convection and conduction in PCMs, with and without fins to aid heat transfer; Stritih looked at the dimensionless Stefan, Rayleigh and Nusselt numbers. Velraj et al. (1997) modelled the crystallisation of PCMs around the tubing, and looked at experimental data, too. An extensive listing of PCM capsule models and experiments is given by Regin et al. (2008).

Supercooling/Subcooling of PCMs

There is a theoretical possibility of heating a PCM until it melts then, in the absence of points for the PCM to nucleate upon, bring it to a temperature below its crystallisation temperature while remaining in liquid state; this would reduce the heat loss rate to the surroundings. A nucleation trigger would be required in order to release the phase change heat; any unmelted crystals from the original heating could take this role so the whole of the container, including the contact surfaces at the edges will need to have melted. This supercooled (or subcooled) state would have inherent instability in that if nucleation is triggered then the heat will be released and if this is unintended then the heat may be lost. The viscosity at the melting point affects the glass-forming ability of the melt and hence its ability to supercool (Duffie and Beckman, 1991).

Often subcooling is problematic since it requires lower heat transfer fluid temperatures to draw the heat out of the phase change material. Yang et al. (2003) found supercooling in both the encapsulated and emulsion tetradecane PCM.

2.2.3 Stationary and Transportable Thermal Energy Storage

The containment of heat storage media can be stationary or transportable. Stationary stores require a supply of HTF to charge and or discharge the store. With DH, there is an easy means by which heat can be distributed and so the heat store could be placed in a fixed location that is strategically chosen to balance supply and demand on the network.

Some technologies rely on the media which are unsuitable for transport, for example stratified water stores could not be used since movement would disturb the stratification. Some store materials may also be too heavy or bulky to transport for example hot water stores on district heating can have a mass of several hundred tonnes due to economies of scale when it comes to constructing and insulating the store.

Waste heat is sometimes generated in remote locations where it would be easier to transport by road or rail to reach points of demand compared to laying new pipelines for HTF. Storch and Hauer (2006) reviewed the economics of transporting heat from an aluminium works and a waste incinerator over up to 10km distance. They found that this approach can be competitive with fossil fuels at 2005 prices, and that economic performance is much more favourable with an adsorption (zeolite) unit than is the case for a phase change material (PCM) unit since the PCM is limited by charge and discharge rates. Following this, trials of a zeolite system are under development and are detailed in Section 0.

2.2.4 UK and EU Policies Affecting Heat Use

In March 2013, the UK Government updated its policy on heat by publishing *The Future of Heat: Meeting the Challenge* (DECC, 2013i) which outlined the actions necessary to meet targets for lowering UK carbon emissions from heating. The Renewable Heat Incentive (RHI) is currently the Government's main tool for delivering the heat strategy with a focus on renewable heat. The UK Government produced a National Heat Map in order to identify areas of high heat demand, see Figure 2-12, and has funded feasibility studies for heat networks around the country (DECC, 2013i).

The Electricity Market Reform Bill is important for the future investments in the UK's energy generating systems. The Contracts for Difference part of the Bill is designed to give investors certainty over future electricity revenues. New biomass and energy from waste plants will only be supported if they are CHP power stations (DECC, 2013o). The Capacity Market legislation in the Bill is designed to ensure there will be enough dispatchable capacity to meet fluctuations of demand (DECC, 2013f). Natural gas CHP units will be eligible for this support allocated through auctions that require generating capacity to be able to operate at times of shortage of capacity. Electricity storage projects can receive support but only hydropower storage projects have so far received support (Energy Storage News, 2015).

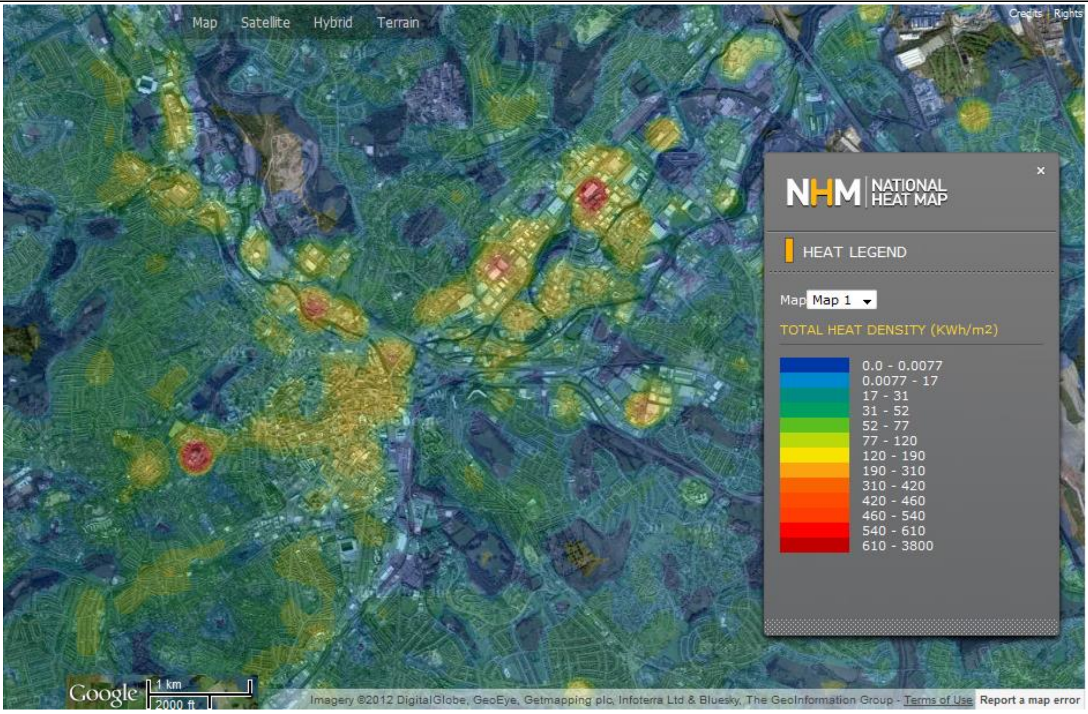

Figure 2-12: Sheffield viewed on DECC's Community Energy Online National Heat Map.
Source: DECC (2012b).

In 2007 and 2008, the European Council agreed ambitious targets known as the “20-20-20” goals which aim, by 2020, to achieve: 20% share of renewable energy in the end-usage, 20% carbon dioxide emission reduction, and 20% energy savings (Taljan et al., 2012). Their strategy includes carbon trading and other regulatory directives. Cogeneration is encouraged at the EU level by Directive 2004/8/CE from the European Parliament (Official Journal of the EU, 2006). The Directive puts an obligation on EU member states to analyse national potentials for CHP and report progress on its development, ensure equitable or preferential access to electricity networks for CHP and review policy with a view to remove barriers to CHP uptake (DECC, 2013h). Member states agreed upon targets for 2030 as a 40% cut in greenhouse gas emissions compared to 1990, at least 27% of energy from renewables and at least 27% reduction in energy consumption compared to business as usual (European Commission, 2016).

In October 2016, the UK government launched a £320 million programme of grants and loans to stimulate the development of district heating projects (BEIS, 2016). The projects can apply for grants or loans if they can demonstrate they are required to meet final investment decision thresholds and these will be assigned on a best value in terms of carbon saving per £1000 invested and on the basis of social net present value (a measure accounting for wider benefits to society such as job creation, reduced fuel poverty and other factors) (*ibid.*). The UK government has also indicated to industry stakeholders that it intends to provide £12 million over three years to develop waste heat recovery projects including feasibility and capital funding due to be consulted upon in early 2017 (ADE, 2016). Projects detailed in this thesis are highly likely to be eligible for this support.

2.3 Modelling of Heat Networks and Storage

The applications of heat storage will be affected by the way energy systems are managed as well as by local geographies. These are complex matters to understand but they will be crucial to maximising economic and environmental benefits of storage applications. Modelling of how a DH system functions is key for the Sheffield case studies in order to identify how heat storage could be integrated.

2.3.1 Heat Demand

The variation of heat demand in buildings affects the viability of heat storage. Historically, UK buildings tend to be charged for gas consumption through monthly manual meter reads. The government-mandated roll-out of automatic meter reading (AMR) for gas meters in the mid to late 2010s (Ofgem, 2016b) has meant that half-hourly or hourly recording of gas consumption is increasingly being used in the UK, particularly in large buildings, allowing heat demand variability to be better understood. Peak heating demands will still have to be estimated for each building as half-hourly metering will not show sufficient resolution to see those demands. The fine resolution of heat demand is particularly important for networks serving a small number of customers where there are stochastic effects, for example the variation due to the switching on and off of hot water taps is explored further by Frederiksen and Werner (2013).

Heat demand forecasts are discussed in detail by Dotzauer (2002), and Werner (1984) studied in detail the variables influencing demand level. With a small number of customers, the stochastic nature of heat demand becomes important and hence stochastic models are needed to give an accurate result while deterministic models can be useful for explaining physical rather than social phenomena (Heller, 2002).

A general look at the variation of demand in Swedish DH systems was undertaken by Gadd and Werner (2013) with typical variations as shown in Figure 2-13. Bogdan and Kopjar (2006) similarly state that the higher peak occurs around 9am and a second peak occurs on the Zagreb DH at around 6pm. Gadd and Werner’s analysis suggests a quantity of heat storage needed at around 17% of the daily supply.

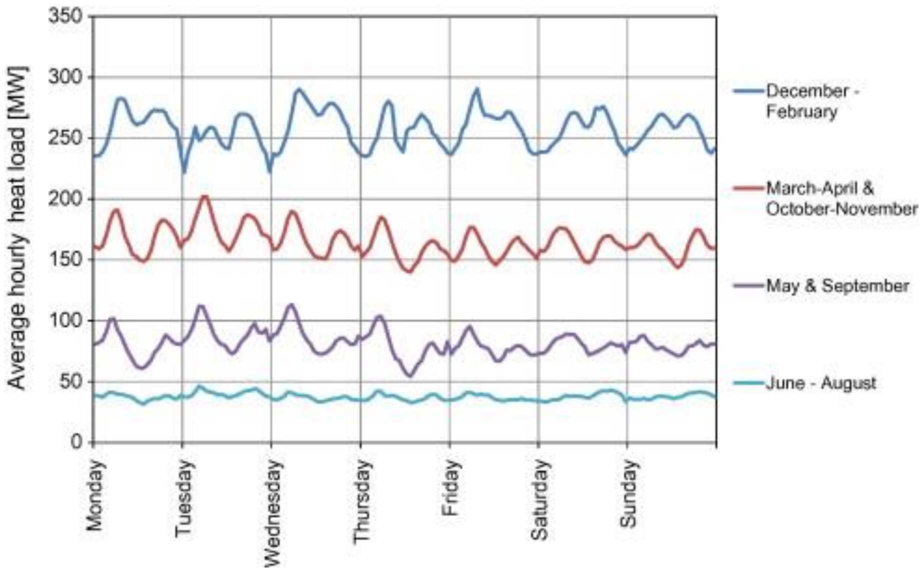

Figure 2-13: Aggregated hour-by-hour load in Swedish district heating systems.
Source: Gadd and Werner (2013).

Hourly recording of load inevitably misses some of the demand variability. The variability of overall DH network demand will depend on both the number of customers and the mix of types of building connected. As an example showing stochastic variations, Wernstedt (2005) gave an example of heat demands of 500 apartments measured over much shorter timescales, as shown in Figure 2-14.

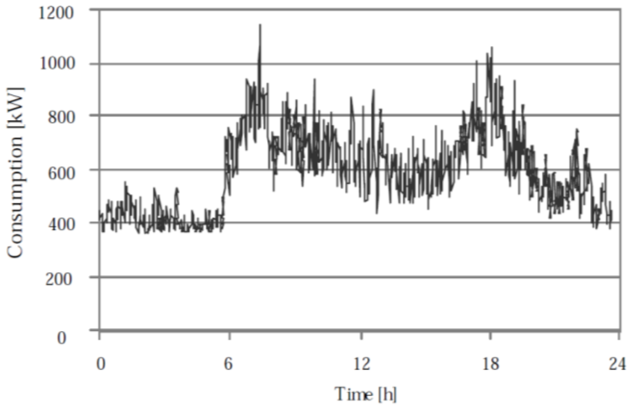

Figure 2-14: Variability of heat demand from a total of 500 apartments.
Source: Wernstedt (2005).

Factors such as solar irradiation and wind effects can alter the heat load. During the heating season, the levels of sunlight are lower meaning the overall effects are small but the level of solar gain a building receives may affect the points of the year at which the decision to switch heating systems on and off is made (Frederiksen and Werner, 2013). In urban areas where building densities are high and DH is prevalent, shading from buildings is more likely to reduce the amount of solar heating (*ibid.*). Gadd and Werner (2013) also note that on warmer days the supply temperature of mains water is likely to be slightly higher and therefore the energy required to produce hot water in buildings is slightly reduced.

Load-Duration Curves

Load duration curves can be created from data showing the variation of heat demand over short timescales by plotting the demand values in descending order. The load duration curve then indicates for how many hours the demand exceeds various threshold levels. These charts can be useful for illustration of how various heat sources are used to meet the heat demand on a DH network.

2.3.2 Network Heat Demand Density and Heat Losses

An important parameter for DH systems is the linear heat density (LHD) defined in Equation 2.1, where L is the length of the DH trench and Q_{total} is the heat demand (Nuytten et al., 2013). The linear heat density can be a useful guide for how economically and environmentally advantageous a DH system is with higher values generally giving better performance. Nuytten et al. note that sustainable values of LHD (economic and environmental) are around 1 MWh/m.a for biomass heating down to 0.2 MWh/m.a for CHP installations. Bohm and Larsen (2004) found that systems with relatively high LHDs could justify higher supply temperatures despite higher losses since the pipe distance over which losses occur will be lower.

$$\text{LHD} = \frac{Q_{total}}{L} \tag{2.1}$$

Network Losses

Taljan et al. (2012) reported that the average heat losses can be as high as 24%. One network with an LHD of 11.7 MWh/m.a was found to have annual heat losses of only 3% (Larsen et al., 2004). Lower amounts of heat supply in summer lead to higher relative heat losses as shown in Table 2-1 from (Bohm et al., 2002).

Table 2-1: Estimated heat losses from Hvalsoe DH system, Denmark.
Source: Bohm et al (2002).

Period	Heat Loss (%)
January 22-28	13
April 8-14	14
July 2-8	40

Thermal Store Losses

Hot water stores for DH are highly insulated in order to minimise heat losses. Ravn and Rygaard (1994) described losses from a heat store on Copenhagen DH using two parts: one in proportion to the energy stored, and the other as a constant loss rate. Even an “empty” store is above the ambient temperature and therefore will lose energy. Some studies neglect heat losses for example by Fragaki et al. (2008) who estimated the losses from the store as 1-2% of the annual DH heat consumption.

Schuchardt et al. (2014) modelled heat loss mechanisms and found that the losses via the wetted wall dominated the overall heat loss, even though the geometry in that study had a low tank height to diameter ratio. They found that losses (including mixing where hot and cold water meet) are only around 6% for a large tank over a four-day period even if using pessimistic assumptions. The losses to the external environment were shown to be well-represented by conduction-only models (*ibid.*).

IEA (2005b) is a useful source for accurately determining the real-life heat losses, and they note that the height to diameter ratio of 1.0 minimises surface area, while higher values reduce the lost volume due to mixing of hot and cold water. The evolution of non-productive volume according to time is explored, with this value being particularly low for height to diameter of 2.5 (IEA, 2005b). After 5 days the thermocline in their model has broadened to 1.16 m (IEA, 2005b).

2.3.3 Feasibility Studies for Heat Storage

Several groups have researched the benefits of integrating heat storage into existing DH systems using historical data; more details of these studies are listed in Table 2-2. A further set of studies investigated the impact of thermal storage on proposed rather than existing CHP and DH facilities; examples of these are listed in Table 2-3 and Table 2-4. Also of note, for a generalised urban area, Marchand et al. (1983) produced a useful paper modelling in detail how CHP could work, as well as the appropriate scale of the DH system, and the appropriate size of thermal store.

Some of the methods listed used include linear programming, this means that the problem can be defined in terms of functions of variables with an objective function that can be maximised or minimised to reach an optimal solution subject to constraints. The presence of logical constraints, such the level of energy stored being within a limited range, fovours the use of mathematical programming (Lozano et al, 2010). The optimal status of a solution can be proven if the problem is linear in its entirety however more often a problem contains non-linear (and/or binary) characteristics (Gustafsson and Karlsson, 1992). Where binary characteristics are modelled, for example with components being in ‘on’ or ‘off’ mode, binary integers can be introduce to a computer code to allow for ‘piecewise linearization however the optimal status of a solution in this circumstance cannot always be proven (Gustaffson and Karlsson). Accordingly, a mixed integer linear program (MILP) or mixed integer nonlinear program (MINLP) emerges (Lozano et al., 2010) depending upon the degree of linearisation undertaken. Introduction of heat storage complicates optimisation through the various possible timescales over which optimisation can occur. The modelling approach undertaken in this thesis is described in Section 3.7.

Where a CHP is feeding a significant fraction of its power to on-site electrical demand there is an option over whether to operate in heat load follow (HLF) or electrical load follow (ELF) modes. Hawkes and Leach (2007) explore these strategies noting that for electrical load follow scenarios minimising any export is only one of the sub-set of ELF modes and may not be cost optimal.

From the papers reviewed, the particular complexity of modelling networks with multiple heat sources is noted. The price of heat from each source may vary according to load factor, and efforts to co-ordinate multiple sources in an effort to maximise income from heat and power sales is not easy. The current situation on Sheffield’s DH network is simpler than some of these models: the CHP heat source is running continuously, except for occasional planned and unplanned outages, with the flexibility to vary its heat output according to heat demands on the network.

Table 2-2: Studies examining heat storage for existing DH systems.

Authors	Application	Objective(s)	Store Capacity	Notes
Bogdan and Kopjar (2006)	Zagreb, Croatia	Improve CHP economics	1500 MWh, 130 MW, 3600m^3	Uses a plant-specific optimisation model in combination with MS Excel's Visual Basic language. Environmental performance improvement calculated, too.
Gadd and Werner (2013)	Swedish DH systems	Apply a general method to find how much storage is needed to smooth out heat demand variation	900 m^3 for each 100 000 MWh per year transmitted	Entails an analysis of hour-by-hour demand data in 20 different systems over entire years. Heat source output set constant over each 24-hour period.
Gustafsson and Karlsson (1992)	Malmö, Sweden	Balance multiple heat inputs, minimise cost.	None	Linear programming used. The capital cost of storage (150 SEK/kWh) was found to be prohibitive, mainly because much of the heat is waste heat at low cost. If storage was already in place (zero capital cost) then 2744 MWh capacity would be optimal.
IEA (2005b)	Not stated	Maximise running of a base load unit while demand fluctuates around its rated output	950 MWh (20,000m^3).	Method for maximising the revenue for switching variable demand to a base load boiler was demonstrated, capacities of 70 to 1750 MWh maximised electricity revenues on varying numbers of days. 950 MWh store capacity would be enough to maximise revenue on 350 days.
Palsson and Ravn (1994)	Esbjerg, Denmark	Maximise income from future stochastic electricity prices.	2111 MWh	Use a "progressive hedging algorithm" to deal with uncertainty over future electricity price.
Ravn and Rygaard (1994)	Copenhagen, Denmark	Optimised scheduling, minimising cost.	8000 GJ =2222 MWh	Optimisation over 48 one-hour periods with constant demands and prices during those hours. Heat losses accounted for. Power limits applied. Extraction, back-pressure and peaking plants and their output-dependent unit costs considered.
Rolfsman (2004)	Linköping, Sweden	Maximise electricity income, reduce running costs.	600 MWh (accumulator), 277 MWh (building stock).	Linear programming used. Considers the use of both an existing accumulator as well as possible use of the building stock. Existing accumulator found to be more than sufficient. Fuel cost increase expected over plant lifetime. Increased electricity price volatility seen to strengthen case.
Streckiene and Andersen (2008)	Germany	Optimise CHP for spot market.	0 (1 MW_e) 250m^3 (for 2MW_e) 650m^3 (for 4MW_e)	energyPRO software used. Adding a CHP to a DH system supplying 30,000 MWh/a, assumed mainly domestic-type demand. CHP runs at rated output only, alongside a gas boiler. €268/m^3 of storage (quoted as same rate as Denmark). Useful economic numbers, payback times of 8/9 years.
Streckiene et al. (2009)	Stadtwerke, Germany	Optimisation for a proposed CHP and thermal store	250 m^3 for 2 MW_e capacity.	Using energyPRO. 30,000 MWh per year of heat delivery. Investment costs €268/m^3 for storage (same as Denmark).

Table 2-3: Studies of potential for CHP and heat storage in new DH or micro-CHP installations in Europe.

Authors	Application	Objective	Store Capacity	Notes
Bianchi et al. (2012)	Northern Italy	Optimise micro-CHP with thermal storage		Some interesting guidance on how overall efficiency varies with electricity to heat output ratio.
Fragaki et al. (2008)	UK	Economic sizing of CHP and thermal store	7.8 MWh	Use energyPRO software. Store in combination with $3MW_e$ gas CHP to meet a 20,000 MWh/year heat load. Heat store more than doubles return on investment. Use estimates of peak and off-peak tariffs for electricity.
Haeseldonckx et al. (2007)	Belgium	Maximise CHP running time, minimise CO_2 emissions	One hour of max. output, and two hours max. output	Residential estate, 40 properties. Small thermal store significantly increased CHP's running time, study shows that multiple small CHP can be treated in aggregate. Negative effects on on/off switching considered. CHP cannot modulate.
Henning (1998)	Swedish case, averaged over 12 systems	Economically optimise balance of heat sources		MODEST software used. Heat storage deemed advantageous to cover peaks, to allow CHP at times of lower demand and to allow heat pumps to work overnight when prices are lower. The mix of heat generation technologies is adjusted by the use of storage.
Kavvadias et al. (2010)	Greece	Optimise the trigeneration system and operating strategy		Customer is a hospital complex with 350 beds. Buffer vessel only helpful in the case of continuous trigeneration operation.
Lindenberger et al. (2000)	Bavaria, Germany	Compare a solar thermal DH with cogeneration	Seasonal solar stores considered	Large solar store costs mean an economic disadvantage. Displacement of high-carbon electricity from the grid means the emissions reduction case for using cogeneration is strong, too.
Lozano et al. (2010)	Zaragosa, Spain	Optimise trigeneration system	48 MWh (hot) 31 MWh (cold)	Mixed integer linear program used. CHCP for 5000 apartments. Assumptions about cooling and heating loads through the course of the day are unclear. System is optimised with and without using thermal energy storage.
Lund and Andersen (2005)	Denmark		4 MW_e with 500 m^3 storage.	Using energyPRO software. Case study 24,000 MWh /year, peak tariffs on weekday mornings, winter evenings, are almost three times the off-peak tariff. Also optimise against the Nord pool spot market. Increased renewable energy use is considered to strengthen case for storage.
Nuytten et al. (2013)			800 kWh (centralised and decentralised)	2355 MWh/year demand in 100 residences. CHP switches on and off. Decentralised stores reduce flexibility as the "weakest link" that empties first forces the CHP unit to switch on.
Pagliarini and Rainieri (2010)	Parma, Italy	Size a CHP and store for University of Parma Campus	1000-1500 m^3	Store shows high economic benefits to operation.
Pini Prato et al. (2012)	North Italy	CHP and DHN modelling to optimise economics		Models using Matlab. Gas CHP, biomass ORC, steel mill cooling circuit combined with heat pump, gas-fired back-up. DH delivery capacity 155 MW_{th}. Engine maps for heat sources used to optimise efficiency; thermal modelling of the network and time delays are important too. Integral-proportional (PI) control applied to the network as a dynamic heat store to assess it potential as such.
Taljan et al. (2012)	Austria	Optimise potential for biomass organic Rankine cycle CHP	None recommended	Matlab's optimisation toolbox and AMPL mathematical language is used for solving equations. Desired 10% rate of return not reached with or without store. Storage cost €672/m^3. Fixed feed-in tariff electricity price.
Zhao et al. (1998)	Danish DH profile, Finnish CHP plant	Minimise total costs, given Danish tariff inputs and real DH demand data		Strong effect of supply temperature on fuel consumption is noted. Significant advantage from storage. Little more detail given.

Table 2-4: Studies of potential for CHP and heat storage in new DH or micro-CHP installations outside Europe.

Authors	Application	Objective	Store Capacity	Notes
Khan et al. (2004)	Bangkok, Thailand	Optimise heat and cooling supply.	300-1250 m^3 cold storage	Absorption chillers implemented. Supply and return temperatures at 7 and 12°C respectively.
Ren et al. (2008)	Japan	Optimise CHP size and store size	6-8 kWh	Mixed integer nonlinear program used. Single building with a small CHP optimised.
Smith et al. (2012)	Chicago, US	Investigate CHP with and without storage for eight commercial building types	Less than one hour of maximum output	Storage is idealised: no power limits or heat losses. Costs meant that storage, if beneficial, was always below 45 minutes of maximum output.

2.3.4 Combining Physical Models of Stores with District Heating System Models

Fracastoro and Poggio (2012) detail the case of Turin, where there is a high-temperature DH system (120°C) with multiple hot water stores. Each 800 m^3 store can provide 56 MW_{th} to the network and there are plans to add eighteen more (*ibid.*). Verda and Colella (2011) model the Turin DH system and calculate the primary energy savings possible through using a heat store. Their work combines a FLUENT model of a hot water tank carrying temperatures up to 118°C with information about DH demand variability, as shown in Figure 2-15. They model an 86 to 90% heat recovery rate, and have powers up to 100 MW for discharge. The two CHP plants are noted to lose 50 and 60 MW of power when each producing their full thermal load of 260 MW compared to operation as electricity-only (*ibid.*).

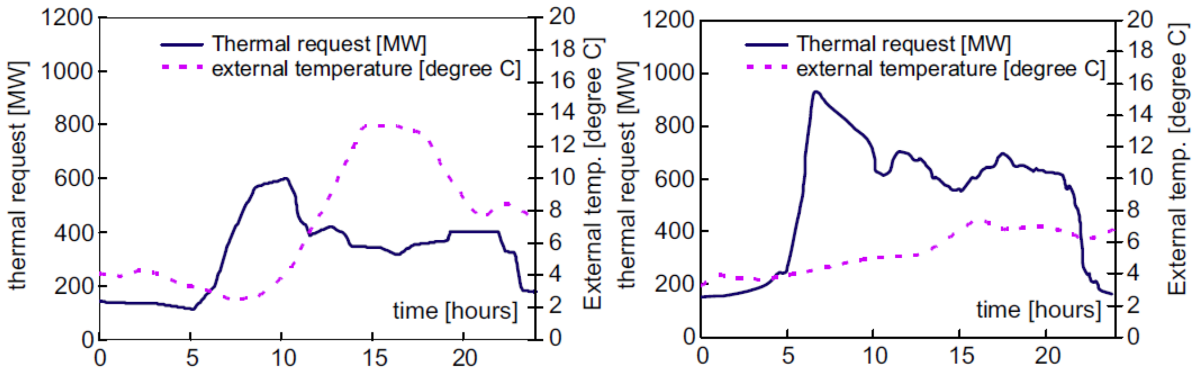

Figure 2-15: The variation of demand and ambient temperatures for a day in November (left) and January (right). Source: Verda and Colella (2011).

Raab et al. (2005) developed models for a buried hot water tank acting as storage in a solar-assisted DH network. One part of the model looks at heat flows in the water tank (a one-dimensional stratified model) along with a three-dimensional mesh for heat flows into and from the surrounding ground. The second part of the model uses TRNSYS simulation software to simulate flows from the solar collector and from the store feed into the DH system, including the losses encountered along the way. They found that the seasonal storage of heat in a buried and insulated store had a round-trip efficiency of 71% (*ibid.*).

2.3.5 Control Systems Modelling

Control systems operation is crucial to the running of modern power plant, and operational data from DH networks will be continuously fed-back to the plant control room for connected plant. The control system for feeding heat into and out of storage would also be crucial for managing the system efficiently. Doležal and Varkop (1970) describe some the control signalling in power stations, as well as the effects of stochastic signals such as the variability of the energy content of fuel entering the boiler.

Wernstedt (2005) models the advantages of the decentralisation of control strategy within a DH network. Wernstedt acknowledges that heat stores can play an important role but in the multi-dimensional model developed goes on to model just-in-time heat production with the consideration of decentralised control whilst meeting local pressure and temperature requirements.

Figure 2-16 shows how the pressure differences between supply and return water varies at different points in the network. If there is any shortfall in heat production then the customers near the plant will still be served adequately, but customers at the network's periphery may not be due to insufficient water pressure.

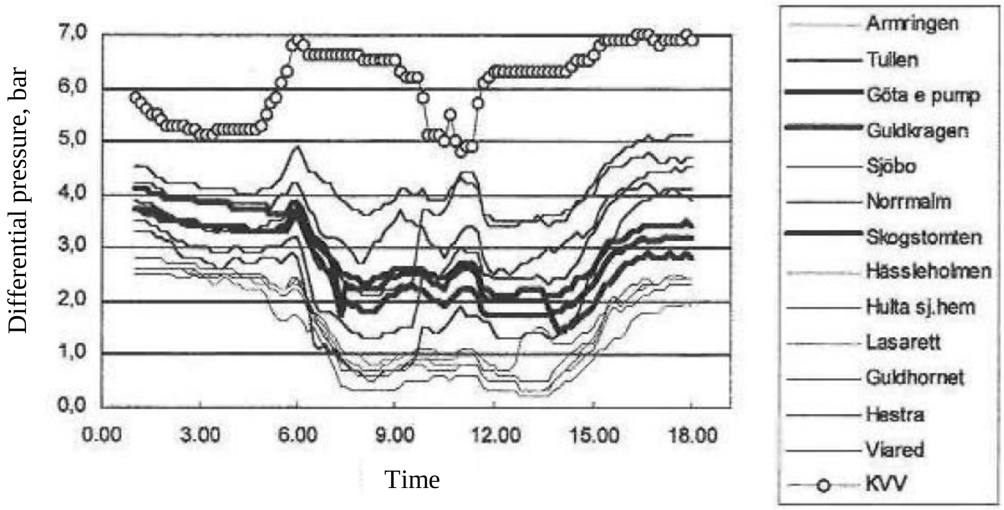

Figure 2-16: Pressure differences between forward and return pipes at various locations over a day. Source: Werner (1997). The dotted line represents the values measured at the central CHP plant.

Wille-Haussmann et al. (2010) compose a model for optimisation of the operation of five CHP units that are centrally coordinated and act as a larger "virtual" power plant in Germany. The system was operated using a thermal store and a back-up boiler. Labidi et al. (2013) provide insights over how to balance the contribution of multiple fuels to a DH system using energy storage, mainly in that case to increase use of wood fuel and reduce gas boiler use. Kitapbayev et al. (2015) optimise a CHP, gas boiler and energy store for DH using stochastic projections for spot prices in the gas and electricity markets and use discrete simulations and regression analysis to identify real-time control strategies.

2.3.6 Physical Models of Networks

In contrast with electrical networks, for DH systems it is important to recognise that the DH water takes time to circulate in the system and thus there is a time lag between production and consumption of heat during which the energy is stored in the DH system. Adjustment of flow rates through the substations feed back quickly to the whole system as pressure adjustments, however any alterations of temperature of the outward or return water take time to reach the substations. The most complex physical models for DH networks in the literature account for the heat losses and hydraulic effects, for example Stevanovic et al. (2009) who developed hydraulic and thermal propagation equations.

Bøhm and Larsen (2004) developed physical-mathematical models for DH networks in Denmark, showing how aggregation of network branches can save computing power when calculating temperature changes and other important effects. Larsen et al. (2004) point to the surface roughness of pipes being a more significant factor for flow resistance than bends in the pipe structure. Bøhm et al. (2002) describe how the fully dynamical models need short time steps of the order 0.5-2 seconds, whereas in "pseudodynamic" models the characteristic of interest is the temperature and the fluid flow is treated in a simpler way.

2.3.7 Water Temperatures and Dynamic Heat Storage

The distribution temperature of DH can be varied to store energy but needs to still be able to meet customer demands. A high DH supply temperature means a lower volume of water needs to be circulated but also higher heat losses. Furthermore a lower flow rate of water means that smaller pipes can be laid and as a result the costs are lower. Jacimovic et al. (1998) describe the constraints on supply temperature in the Belgrade DH system where there is a mix of direct and indirect (via heat exchanger) connections to consumers. Supply temperatures can be lowered in summer, as shown in Figure 2-17, allowing higher efficiencies at the power station and lower heat losses from pipes. Stresses on pipes are higher with elevated temperatures so care is required and management of heat and pressure in the pipes can be complex (IEA, 2005a). More than half of Finnish DH operators interviewed about this approach were favourable to it and this was estimated to represent 1500 MWh of storage capacity in Finland (IEA, 2005a).

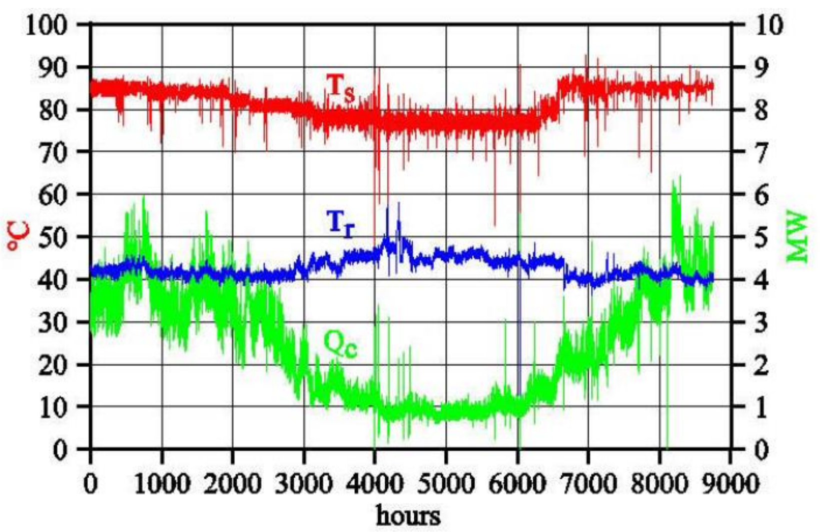

Figure 2-17: The seasonality of heat load on the Hvalsoe DH system in 1998, as well as the narrowing of the difference in supply and return temperatures in summer months.
Source: Bohm et al (2002).

Basciotti et al. (2012) model the storage capacity of pipework for the sake of peak-shaving, finding the heat capacity in Equation 2.2, where *C* is the heat capacity, equal to the sum over N different pipe types of the products of density (ρ), specific heat capacity (c_p), pipe length (L_i) and the cross sectional area which is defined by the diameter (D_i).

$$C = \sum_{i=1}^{N} \rho . c_p . L_i . \pi \frac{{D_i}^2}{4} \tag{2.2}$$

Basciotti et al. (2012) calculated a storage capacity of around 20 kWh per kilometre per degree of temperature change; this is only enough to shift supply within a timescale of hours for the system under study. There are complex feedback loops in the models since consumers take smaller flow rates to get the same amount of heat and so elevated temperatures then circulate slower; some of the feedbacks are shown in Figure 2-18.

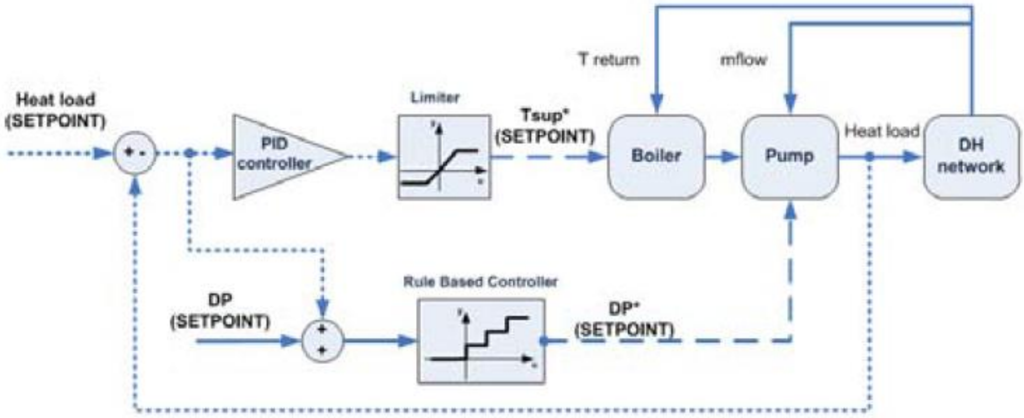

Figure 2-18: An example control system for using district heating pipes for thermal storage.
Source: Basciotti et al. (2012).

Basciotti et al. (2012) showed that optimising this control could reduce the daily peak load by up to 15% and reduce fuel costs by around 2%. This effect was also investigated by Wigbels et al. (2002) and Pini Prato et al. (2012). Pini Prato et al. found the storage capacity to be 5.18 MWh in a network which delivers 22.8 GWh of heat per year.

2.4 High Temperature Store Technology (>150°C)

Many heat storage applications require technologies to work at well over 100°C, these can be quite different in character to those used at lower temperatures. This section reviews the storage technologies available for temperatures higher than those at which hot water heat networks operate; these technologies could be applied at the network's heat sources.

2.4.1 Sensible Storage

The temperature of a medium affects its physical properties and the best material can depend on a number of factors. Khare et al. (2013) demonstrated software designed for selecting the best materials for high temperature thermal storage from an increasingly diverse range of new materials, by considering factors including energy density, conductivity, environmental impact and material strength.

Ceramics and natural stone can be used as high-temperature sensible thermal stores, for example in furnace regenerators where heat captured from flue can be passed to air entering the furnace by periodically switching the air-flow directions. Concrete also can be used at high temperatures of around 400°C, but Laing et al. (2011) note the importance of commissioning such concrete with care allowing time for moisture to escape during heating avoiding damage to the concrete's structure.

One project in Germany captures heat from a gas turbine exhaust and stores that heat at up to 500°C in ceramic bricks and natural stone fillings with the intention of giving gas-turbine CHP plants greater flexibility by liberating them from heat load follow operation (RWE, 2012). Daschner et al. (2012) created a pebble bed system to capture exhaust heat at biomass or waste CHP plants to raise the inlet temperatures for the electricity-generating turbines to improve electrical efficiency and provide similar CHP flexibility.

In June 2012, the UK's Energy Technologies Institute announced investment of £14 million in a five-year demonstration project for pumped heat electricity storage (PHES). This is where electricity is absorbed to create a temperature differential between two silos full of gravel (500°C in the hot silo and minus 160°C in the cold silo). The heat pump will then run in reverse as a heat engine in order to regenerate electricity in order to produce 1.5MW discharge and store 6MWh (ETI, 2012). Unfortunately, Isentropic Ltd went into administration in January 2016 with activities being passed to the Sir Joseph Swan Centre for Energy Research at Newcastle University (Isentropic Ltd, 2016).

Organic oils can be for heat storage up to around 350°C, but any higher and there are concerns over flammability (Hasnain, 1998). Mineral oil can be used to store at high temperatures and low pressures and may be applicable in heat recovery from industry. Medrano et al. (2010) describe the use of thermal oil to store heat at 307°C from a solar collector in California; the oil then passes a power generation block to discharge to 240°C before being recharged with solar heat. Later development of the solar collectors worked at temperatures that were too high to use this oil without pressurised tanks and there were also flammability issues, hence the type of storage medium was changed to molten salt (Medrano et al., 2010). The oils can be used below around 350 to 400 °C and specific heat capacities are 50-60 % of that for water (Herrmann and Kearney, 2002).

Molten salts can be used for sensible heat storage and are generally stable up to around 500°C (Tian and Zhao, 2013). The high freezing points of these substances mean that they can be difficult to handle, for example requiring lots of insulation on pipework and heat exchangers and heat tracing in some instances (Khare et al, 2013).

Ionic liquids can be used as high temperature thermal stores since their very low vapour pressures mean they remain liquid at very high temperatures (Chen et al., 2009); some example ionic liquid molecules are shown in Figure 2-19. There are major barriers for ionic liquids in terms of expense of manufacture (Smiglak et al, 2014).

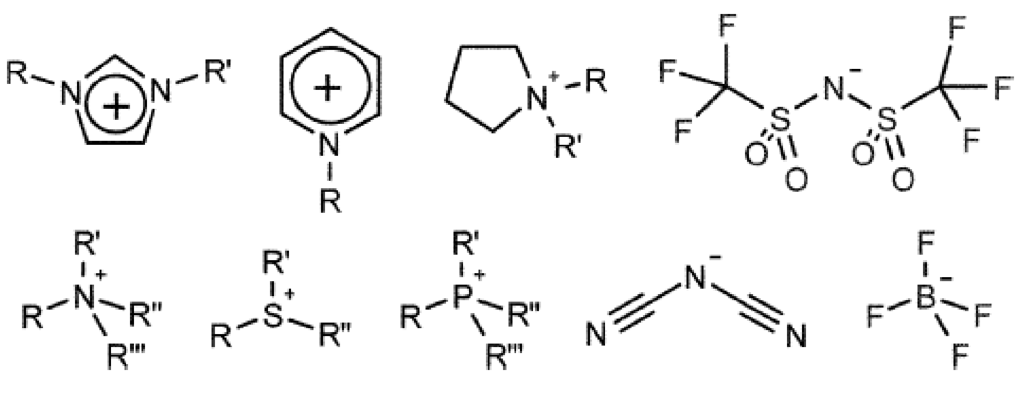

Figure 2-19: Example structures for ionic liquid anions and cations.
Source: Wishart (2009).

2.4.2 Steam Accumulators

Steam use for the provision of high temperature heat is common across industry and is used in power generation processes with steam turbines. Steam accumulators are used in industry as a buffer store for saturated steam for example, to allow higher steam supply rates over short periods without having to invest in more steam boilers. Figure 2-20 shows a typical steam accumulator, where steam is bubbled into the liquid water causing both evaporation and increasing temperature and pressure inside the reinforced vessel. Temperature and pressure in the vessel rise while charging then when steam is discharged, the falling pressure inside the vessel causes some hot water to turn to steam meaning that the steam volume stored can be much greater than the vessel volume. The dimensions of the accumulator are important as they affect the surface area of the liquid water and this in turn affects the power of discharge (Spirax Sarco, 2002). Characteristic energy storage densities are 20-30 kWh/m^3 and accumulators operating at temperatures of 400°C and pressures up to 100 bar have been used in solar heating plants (Steinmann and Eck, 2006) (Medrano et al., 2010). Heat exchangers can be incorporated into the accumulator volume for charging and accordingly this heat transfer fluid can circulate at a lower pressure.

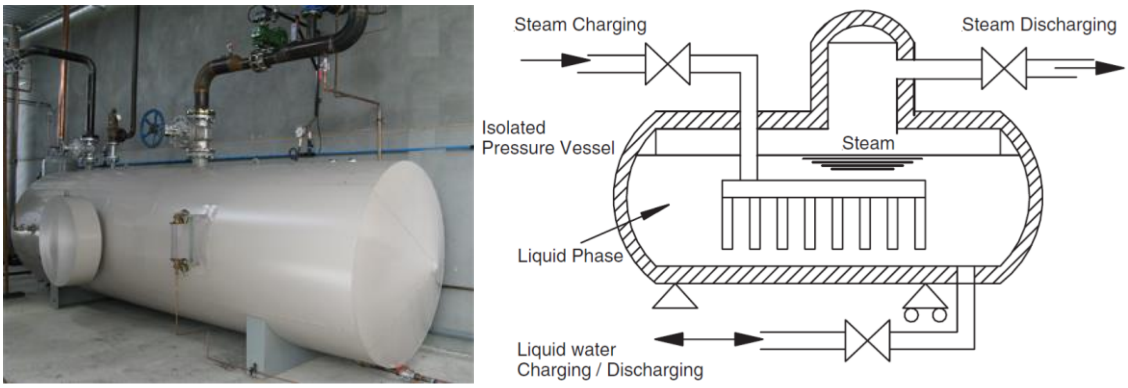

Figure 2-20: A 10,000 litre volume steam accumulator (left) and schematic (right).
Sources: Photo from Forbes and Hunt Boilers (2009), schematic from Tamme et al. (2008).

Steam pressure drops during steam accumulator discharge which can be problematic for processes requiring constant pressure. Steinmann and Eck (2006) suggest feeding water into the base of the accumulator to keep pressure up whilst minimising the liquid mixing so as not to affect evaporation temperatures. Tamme et al. (2008) suggest the incorporation of phase change materials to counter any drop in temperature by the release of latent heat. Swithenbank et al. (2013) suggest the use of modern materials to store supercritical steam in an accumulator where a displacement volume of pressurised water is used to maintain pressure during discharge.

There are on-going research projects to look at very high steam temperatures in power plants. Higher operational temperatures have a thermodynamic advantage in terms of efficiency, as explained in Section 3.1.4. Research projects investigating high pressure steam include the European COST 536 programme and the AD700 programme both aiming to take advantage of new material technologies (DTI, 2006). The AD600 programme led to some innovations around the steam cycle at these temperatures and in 2008 E.ON was thought to be willing to pilot the 700°C steam concept at a plant in

Germany (Modern Power Systems, 2008), but by 2011 it was clear the plant would work on lower temperature steam (E.ON, 2011b).

2.4.3 Latent Heat Storage

Phase change materials (PCMs) generally have greater storage capacities of 100-200 kWh/m^3 compared to 20-30 kWh/m^3 for hot water (Hauer, 2013). Low thermal conductivities can however limit charge and discharge rates. During PCM charging, heat transfer rates change as the material around the heating element melts meaning greater heat transfer. During discharge, the PCM often solidifies on the cooling element first and the heat transfer rate falls accordingly (Steinmann et al., 2010).

From 1995 to 1999 a solar array in California ran with molten salt storage which melted at 207°C and was stable up to 600°C (Medrano et al., 2010). That plant had round trip storage efficiencies of 90% using well-insulated tanks of salt (Medrano et al., 2010). The Andasol 1 solar plant in Spain runs with 28,500 tonnes of metal nitrate salt, enough to store 7.5 hours of full output of power (IEEE Spectrum, 2008).

Sodium hydroxide salt has a melting point of 320°C so can accept heat from high-temperature steam but its highly corrosive nature makes use difficult (Chan and Russell, 2011). Jonemann (2013) reports a detailed account of design and construction of a high temperature salt store, finding corrosion from oxygen in the salt forming oxides on the metal containers.

Tamme et al. (2008) conducted experiments where increased thermal conductivities were achieved by use of graphite in a composite with the molten salt PCM, like in Figure 2-21. Material is manufactured by cold compression and drilled to allow insertion of the heat-exchanger. However, in initial experiments around 40% of the nitrate salt separated from the graphite composite. Nitrate salt creeping onto the metalwork was thought to be one of the main factors in the poor performance of the material (Steinmann et al, 2010).

Following this, a “sandwich” concept incorporating layers of heat-conducting materials into the PCM was developed; best performance for improved charging rates was found by using graphite layers of 1mm thickness. One limitation was found to be that the graphite is unstable with the metal nitrates above 250°C, so metallic fins should be used to boost conductivity at these higher temperatures (Steinmann et al., 2010).

Laing et al. (2011) developed a system that combines both sensible and latent heat storage for the storage of heat from high-temperature steam transitions. Other researchers have investigated alternatives such as metal foam endostructures, see Figure 2-22 (Wu and Zhao, 2011). The foam helped heat transfer in the solid state but inhibited natural convection in the liquid state. Experiments also showed corrosion of the foam from the sodium nitrate salt (*ibid.*).

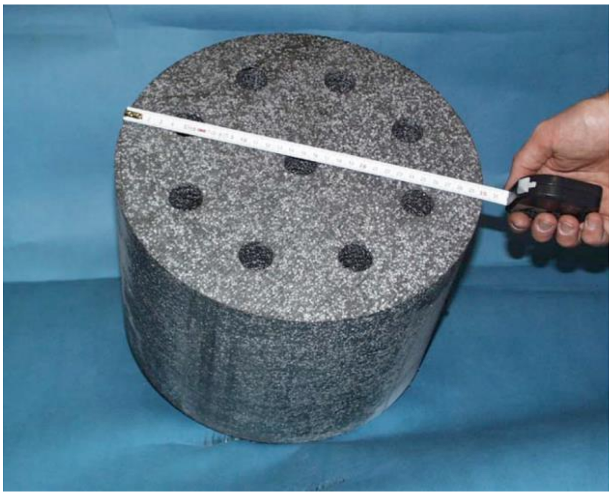

Figure 2-21: A composite phase change material consisting of KNO_3-$NaNO_3$ and expanded graphite.
Source: Steinmann et al. (2010)

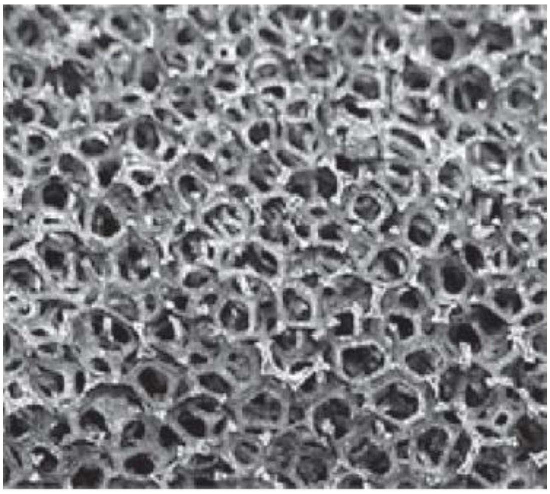

Figure 2-22: A metal foam endostructure trialled for conductivity enhancement.
Source: Wu and Zhao (2011).

An innovative PCM system being tested where a screw mechanism transfers a solid granulated PCM through a heat exchange surface into a molten tank to store the energy from solar thermal generators is shown in Figure 2-23. The direction of the screw can be reversed to carry material from the hot to the cold tank and give off steam for power generation (E.ON, 2012). This novel system breaks the link between the size of the heat exchange surface and the size of the store which is important since the heat exchange surface with finned structures can be expensive to manufacture. The primary difficulty with this technology is to create a solid that can easily be moved by an Archimedes screw.

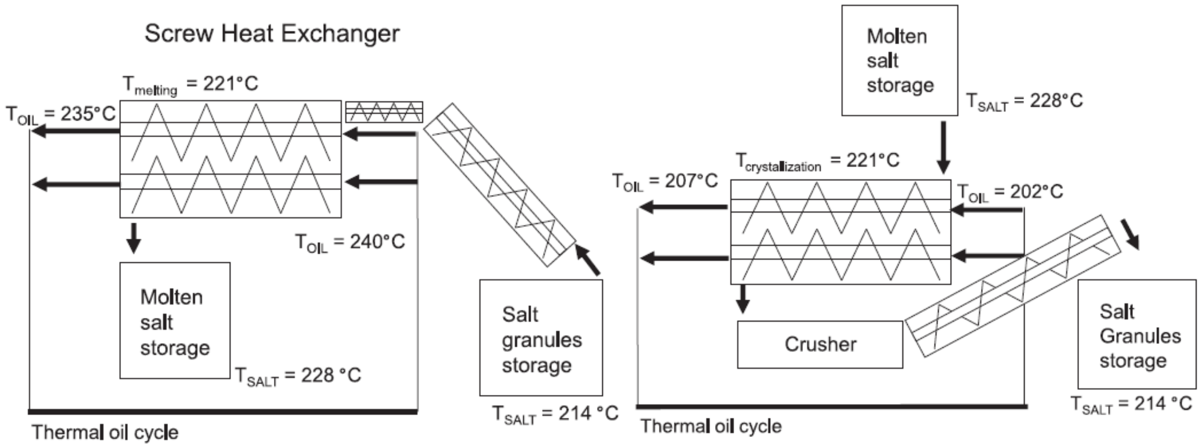

Fig. 6. Layout of $Q = 5$ kW storage system as installed in the laboratory; left: charging of storage; right: discharging of storage.

Figure 2-23: A screw heat exchanger design for high temperature phase change materials.
Source: Zipf et al. (2012).

Since 2011, Steinmann and Laing have been working on a project with E.ON using high temperature stores with alternative, lower cost materials (E.ON, 2012) noting how molten salts are much more costly than these basic materials at around ten times the cost (*ibid.*).

2.4.4 Thermochemistry

The bonds of molecules contain energy and thus reactions that alter the configurations of the molecules result in changes to that internal energy. Hauer (2013) reviews the thermal chemical reactions which may be useful, and these are transcribed in Table 2-5. Physical-chemical changes tend to hold even more energy per unit mass than phase changes. Chemical stores with high energy densities may have the best potential for transportable stores, and attempts to commercialise such technologies will be discussed.

Table 2-5: Some chemical reactions of interest for heat storage.
Source: Hauer (2013).

Reaction		Reaction Temperature (°C)	Energy Density (kJ/kg)
Methane Steam Reforming	$CH_{4(g)} + H_2O_{(g)} \leftrightarrow CO_{(g)} + 3H_{2(g)}$	480-1195	6053
Ammonia Dissociation	$2NH_{3(g)} \leftrightarrow N_{2(g)} + 3H_{2(g)}$	400-500	3940
Dehydrogenation of Metal Hydrides	$MgH_{2(s)} \leftrightarrow Mg_{(s)} + H_{2(g)}$	250-500	3079 (heat store) 9000 (H_2 store)
Dehydration of Metal Hydroxides	$Ca(OH)_{2(s)} \leftrightarrow CaO_{(s)} + H_2O_{(g)}$	405-572	1415
Catalytic Dissociation	$2SO_{3(g)} \leftrightarrow 2SO_{2(g)} + O_{2(g)}$	520-960	1235

Chemical reactions in which the products are in a different phase to the reactants will have high energy storage density as a lot of energy is generally needed to overcome inter-molecular forces and change the phase (Chan et al, 2013).

The characteristic temperatures at which the reactions happen relates to the amount of kinetic energy that the reactant particles need to collide successfully and react with each other. Elevated pressures may be needed to make the reactions move in a particular direction, in order to get the required amount of product. Catalysts can help achieve lower reaction temperatures and pressures.

Chemical reactions can store in the range of 700 to 1200 kWh/m^3 of energy, with temperatures of several hundred degrees (Tian and Zhao, 2013). Higher temperature applications mean that chemical reactions may work well with industrial processes. Problems can occur when the reactants undergo undesirable changes, such as corrosion reactions with the container vessel. The use of chemicals also has environmental risks if the chemical waste is hazardous, and the chemicals may also be fossil-fuel derived and there are likely to be carbon emissions associated with manufacture.

Figure 2-24 shows beads of two types of zeolite (an aluminosilicate mineral) which is a strong adsorber of water. These beads were developed to have a high surface area allowing greater energy storage densities; latest results can be viewed in (Jänchen and Stach, 2012), where significantly higher energy densities than water are achieved but cost is still a big issue.

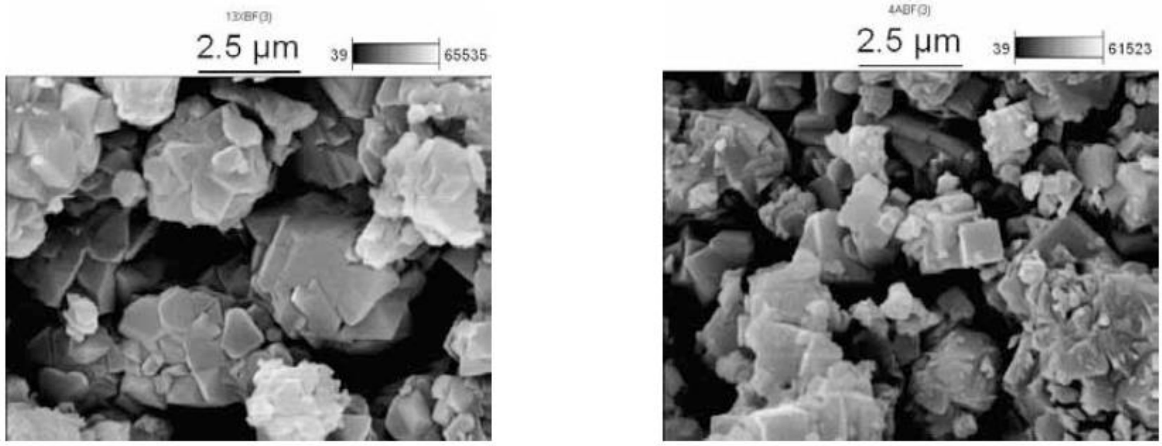

Figure 2-24: Zeolite sieve beads manufactured for high surface areas.
Source: IEA (2010).

Hauer (2002) compares the functioning of zeolite and silica gel sorption systems with varying temperature changes and humidity; also stating that adsorbents will have to be suited to working in high temperature and humid environments so stability will be crucial.

Hauer (2007) explains that adsorption processes are suitable for the transportation of heat with the potential for capturing industrial heat and transporting it to other applications in particular, drying processes. Humidifying the hot, dry air can lead to cooling applications (Hauer, 2007). Table 2-11 shows candidate dehydration reactions considered by KTH (Swedish Royal Institute for Technology) for heat transport by road from a steelworks to a city utility plant (Hauer et al, 2010). Note how some reactions occur over multiple steps and consequently the same hydrated substrate can accept heat at two different temperatures and undergo chemical change to store energy. A magnesium sulphate ($MgSO_4$) hydration unit with 20 tonnes mass when hydrated could store approximately 10MWh (Hauer et al, 2010). The combination of $MgSO_4$ with zeolite materials has achieved capacities of 166 kWh/m^3 (Mette et al., 2012).

Table 2-6: Possible dehydration reactions for heat storage.
Source: Hauer et al. (2010).

Temp (°C)	Reaction	$\Delta H_{react,} H_2O(g)$ (kWh/t$_{product}$)	$\Delta H_{react,} H_2O(l)$ (kWh/t$_{product}$)
100	$Na_2SO_4.10H_2O \leftrightarrow Na_2SO_4 + 10H_2O$	1039	178
128	$CaSO_4.2H_2O \leftrightarrow CaSO_4.\frac{1}{2}H_2O + \frac{3}{2}H_2O$	165	30
150	$MgSO_4.7H_2O \leftrightarrow MgSO_4.1H_2O + 6H_2O$	867	256
163	$CaSO_4.2H_2O \leftrightarrow CaSO_4 + 2H_2O$	214	34
200	$MgSO_4.7H_2O \leftrightarrow MgSO_4 + 7H_2O$	974	261
350	$Mg(OH)_2 \leftrightarrow MgO + H_2O$	558	252
580	$Ca(OH)_2 \leftrightarrow CaO + H_2O$	540	322

Table 2-6 shows, by comparing the two right-hand columns, that the best performance for the rehydration reactions is achieved when water enters the dry salt store as steam (third column). In this instance, heat energy is not taken from the salt to evaporate the water. Typically only 40% of the heat can be retrieved with liquid water (Hauer et al, 2010). The power of discharge and charge depend upon the water vapour pressure (Rammelberg et al., 2012).

The upgrade of steam to hot, dry air means that these sorption systems act as *chemical heat pumps,* upgrading low-temperature heat in moist air. There is a potential for such a unit to absorb low-grade heat from a building, providing cooling, as long as there is a sink for the hot dry air. The hot and dry air product is probably best suited for local drying applications (Hauer et al, 2010). Liquid sorption materials are possible too; one example is lithium chloride researched at the University of Minnesota (IEA, 2010).

Thermal Dehydrogenation of Metal Hydrides

Reiser et al. (2000) and Felderhoff and Bogdanović (2009) propose the use of metal hydrides as heat stores. Figure 2-25 shows how the temperature of hydrogen dissociation from magnesium hydride rises with pressure. The shaded sector represents conditions for heat absorption and the light section the conditions for heat release. This reaction needs high temperatures and pressures in order to occur and preferably a good catalyst to increase rates of absorption and desorption of heat.

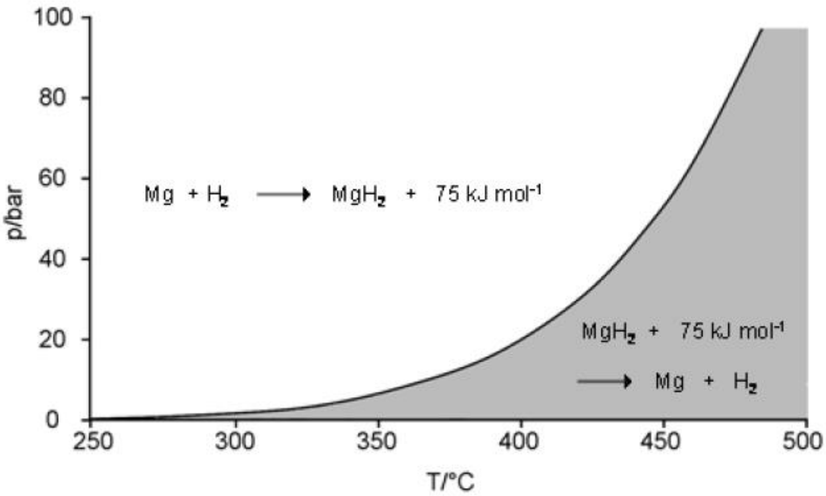

Figure 2-25: Dissociation pressure curve of magnesium hydride.
Source: Felderhoff and Bogdanović (2009)

Oxidation and Reduction of Metals

The use of thermal decomposition of metal oxides was discussed by Duffie and Beckman (1991). They considered two reactions; for potassium oxide occurring at 300 to 800°C as in Equation 2.3 and lead oxide at 300 to 350°C as in Equation 2.4. Both reactions cause corrosion at those high temperatures (*ibid.*).

$$4KO_2 \leftrightarrow 2K_2O + 3O_2,\ \Delta H = 2.1MJ/kg \quad (2.3)$$

$$2PbO_2 \leftrightarrow 2PbO + O_2,\ \Delta H = 0.26MJ/kg \quad (2.4)$$

Dehydration Reactions

Mobile applications for this high energy density technology have also been explored. Figure 2-26 represents a concept developed by ZAE Bayern to use a zeolite sorption technology to carry waste heat which was due for trials in 2012/13 (zae-bayern.de, 2013) but results could not be found. The specification aims to achieve 1MW discharge rate discharging 20,000 m^3/h of dry air for the purpose of starch drying (Hauer et al., 2010).

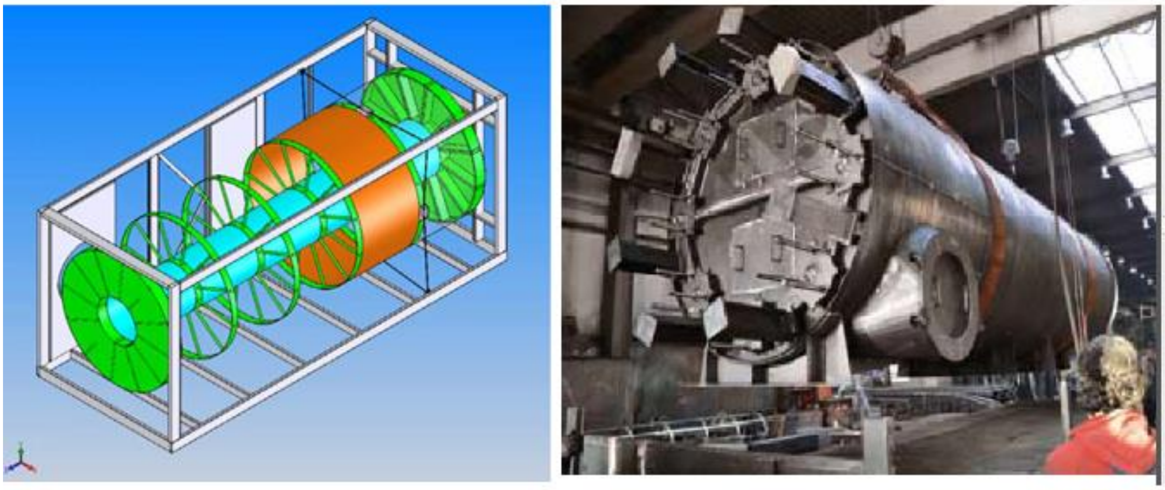

Figure 2-26: Zeolite freight container portable absorption store concept (left) and in production (right).
Source: Hauer et al (2010), ZAE Bayern (2011).

Their concept developed into a 14 tonne pilot store operating over 7km distance as in Figure 2-27; the module has a capacity of approximately 2 MWh and went into operation in September 2012 (MVA Hamm, 2012). Based on 200 storage cycles per year, the final cost of delivered heat in this project will be around €50/MWh (Krönauer et al, 2012).

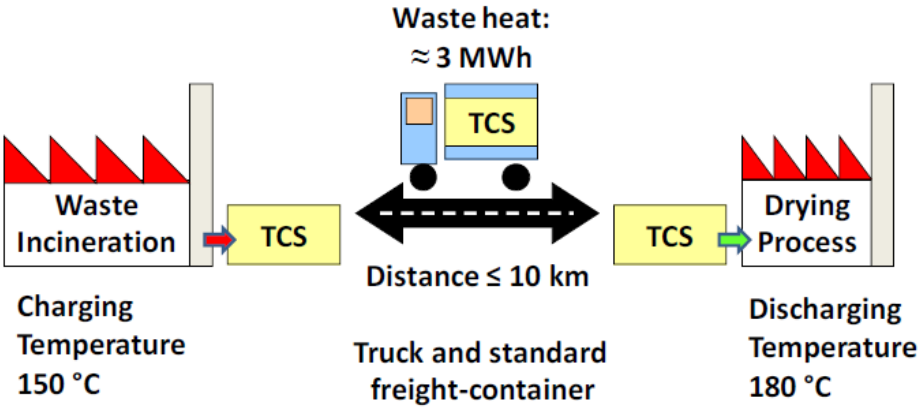

Figure 2-27: Heat transport using an absorption thermo-chemical store (TCS).
Source: Hauer (2013).

2.5 Medium Temperature Store Technology (60°C – 150°C)

This review of medium-temperature thermal energy storage technologies covers stores at temperatures between 60°C and 150°C. This range covers temperatures that can be carried by liquid water, which can be superheated over 100°C if the water is pressurised with a lower limit of 60°C approximating to low return temperatures seen in some DH systems. Figure 2-28 shows the typical capacity of a range of materials for storage up to 200°C. Phase Change Materials and thermochemical materials show greater energy densities than water; however they also generally have greater cost.

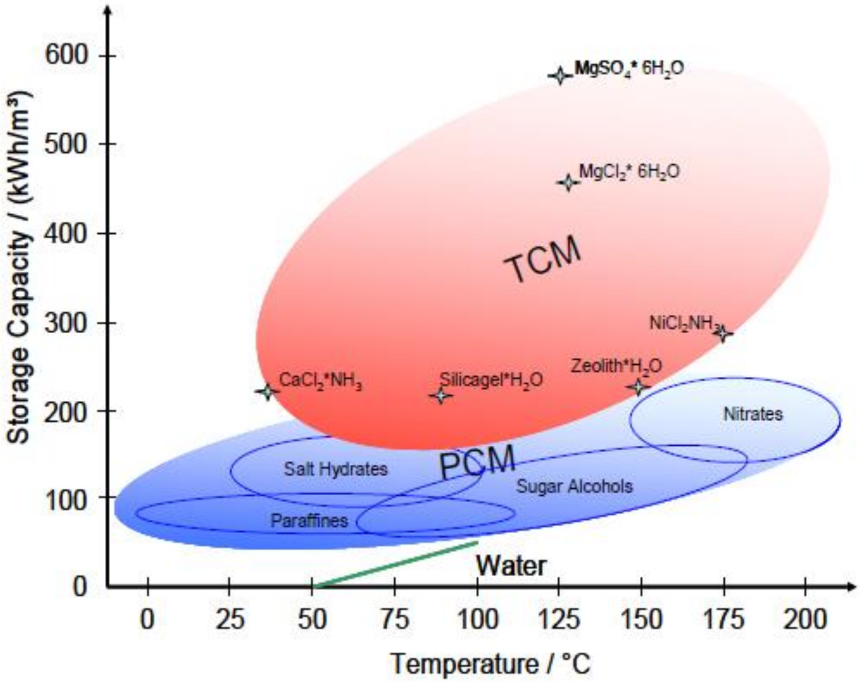

Figure 2-28: Storage capacity versus temperature for various heat stores
Source: Hauer (2013).

The characteristics of a material will often change with temperature meaning that only a certain range of temperatures are suitable for operating the material as a heat store. Outside the working range a sensible store material may undergo phase change which may cause problems such as the large amount of expansion seen in a liquid to vapour transition.

2.5.1 Hot Water Storage

Hot water storage dominates the thermal energy storage market due to its use in both sanitary hot water applications and for circulation in building heating systems. A significant benefit of using hot water storage in district heating (DH) is that the storage medium is the same as that flowing through the pipes to supply heat to the buildings. This means that the loss of temperature and energy associated with heat transfer between different media is avoided. The physical discharge of the media itself allows for large thermal power outputs of over 100 MW (Verda and Colella, 2011).

In DH systems it is possible to store hot (supply) or cooler (return) water and the most common solution is to store both the same tank with separation maintained by density differences with the hot water at the top and cooler water at the bottom. It is possible to store the two separately but the costs and space requirement rise while the benefit of reduced losses due to mixing is not significant. It is however important that water enters such a tank at low velocity (using a nozzle or diffuser and multiple inlets) to minimise the amount of mixing of hot and cold layers (IEA, 2005b). Around 90% of the store tends to be usable capacity since the region with a strong temperature gradient between the hot and cold parts is not useful (Streckiene et al., 2009). The chosen height to diameter ratio of the tank compensates the tank’s surface area against the cross-sectional area where there is the mixed temperature layer.

Sealed tanks on DH networks need to be protected from crumpling if there is a leak in the system and the pressure falls (IEA, 2005b). A pocket of inert vapour is usually used to stop oxygen entering into the system and causing corrosion (ibid.). For high temperatures a steam cushion is a good option but with low temperatures, such as solar-generated hot water, a pocket of nitrogen is better (IEA, 2008). Plastic liners in general cannot handle temperatures over 80°C and so metal or concrete liner is required (Ochs et al., 2008).

Bermed tanks, where soil is packed against the walls of an above-ground tank, have good economics (Pinel et al, 2011) although they are less thermally efficient than fully buried tanks. With buried tanks, extra measures must be taken to prevent the insulation getting wet.

Scales of Application

As the size of a hot water tank grows, the volume increases faster than the surface area and so the heat losses fall in comparison with the storage capacity. Hence with DH it usually makes more sense to have a large central store of hot water, compared to distributed stores.

For a DH network, a common characteristic is that connected buildings tend to return water to the network at 60-70 °C. This limit means that higher supply temperatures are needed to minimise the pipe diameters installed and therefore the capital expenditure. Lower DH supply temperatures can reduce heat losses and allow more efficient heat generation but the hot water storage volume required rises due to smaller difference between the energy in the hot and cold water. Very large capacities are sometimes available, such as in an underground cavern to store hot water. Large above-ground stores have been used for pioneering, low-temperature solar thermal DH projects to make the most of large supplies of solar heating in summer and store this until winter months.

The need in some DH systems to have pressurised stores in order to prevent the hot water from boiling means that pre-stressed pressure vessels are required and these need to comply with pressure vessel regulations. These vessels are manufactured away from the site and must usually be transported by road. This road transport places a limit of 3.5 metres on the tank diameter; otherwise a police escort is needed for the vehicle (Martin and Thornley, 2013). The consequence of this is that pressurised stores will need to consist of multiple tall and thin tanks leading to high relatively high surface area and cost.

Integrated Heat Exchangers

If included in water store tanks, heat exchangers tend to be located at the lower part of the tank where cooler water resides in order to take advantage of the greater temperature differences for heat transfer. This however reduces stratification, in turn reducing useful energy (exergy) content (Pinel et al, 2011). External heat exchangers can wrap around the surface of the tank; these are easier to incorporate but there is greater chance of losing heat from the system. Mantle-type heat exchangers have a double-wall structure through which the heat transfer fluid can flow (Pinel et al, 2011); this gives a high heat transfer area but can be hard to engineer. Heat exchangers in the tanks were modelled and compared with experiment for various sizes shapes and orientations of exchangers by Mote and Probert (1991).

Stratification

Stratified water tanks store more exergy than well-mixed tanks of water (Pinel et al, 2011); water can be injected and extracted at various depths to maintain it. Well-stratified stores are easier to transfer heat to when almost fully-charged since cooler water returning to the heat source will pick up heat better; and easier to draw heat from when nearly depleted (Pinel et al, 2011). Larger heat losses in tanks lead to greater amounts of circulation and less stratification (Hess and Miller, 1982).

Methods to model the development of the mixed-temperature zone in stratified hot water tanks are described in (IEA, 2005b). The mathematical model results for this widening zone are shown in Figure 2-29, starting at time of zero with upper and lower temperatures of 100°C and 50°C respectively. There is no charge or discharge of the tank assumed in the displayed model.

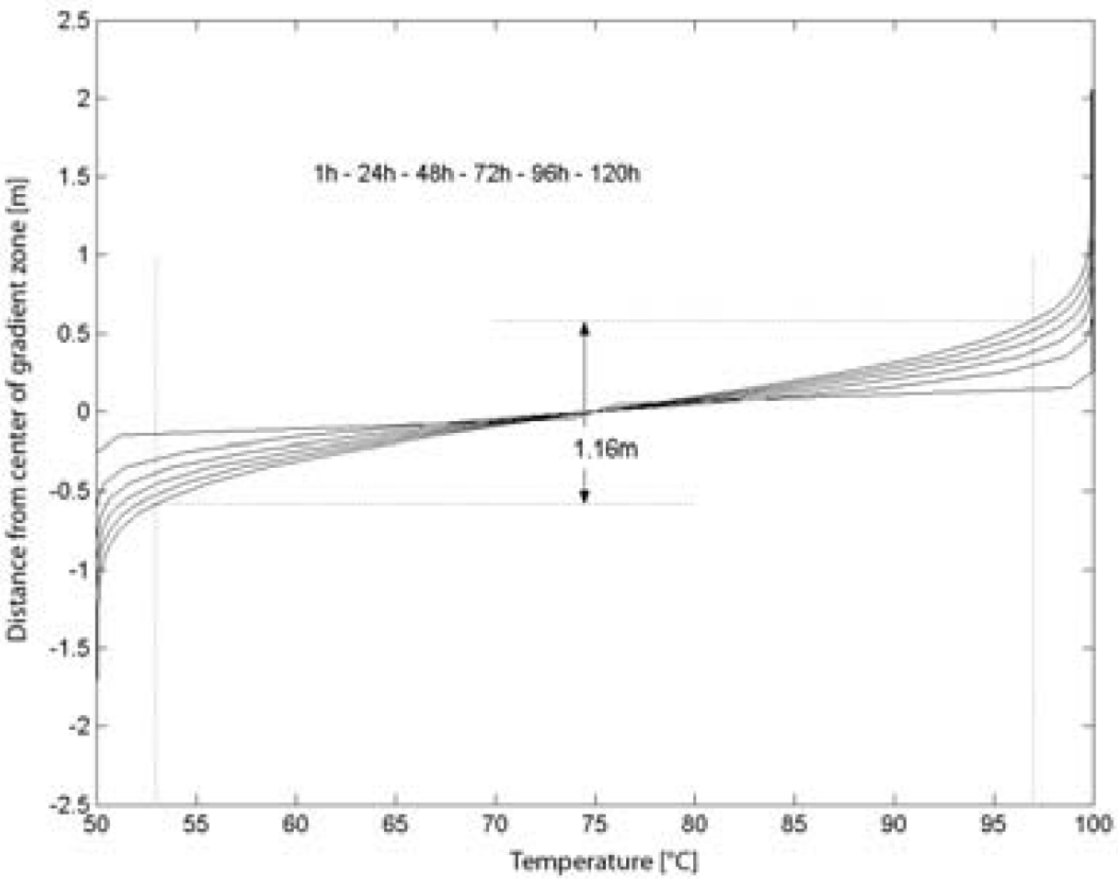

Figure 2-29: Rresults from a model for how thermocline develops over time in a 10m diameter tank. Source: IEA (2005b).

De Cesaro Oliveski et al. (2003) compared the one and two dimensional computational models to experimental results including how the thermocline in the tank descends over time. Campos Celador et al. (2011) discuss how variation of stratification affects the economics of a CHP plant with a thermal store. They show that it is economical to maximise the amount of stratification, as well as considering the exergy flows in the system which, although they show similar performance in exergy terms with the different stratifications, differ in the locations and magnitudes of exergy loss.

Davidson et al. (1994) use a dimensionless MIX-number to quantify stratification, essentially comparing the observed heat distribution to a perfectly stratified store with the same amount of energy. The work of Anderson et al. (2007) extends this concept to a situation where the tank is losing heat and so the fully-stratified state against which comparison is made, is losing heat all the while. Rysanek (2009) carried out a fluid dynamic analysis of water entering a tank and encountering diffusers, and the resulting effect upon stratification. Mehling et al (2003) investigated the effect upon stratification of incorporating a phase change material into a hot water tank.

Hot Water Store Examples

Figure 2-30 shows the range of sizes of stores that are linked to heat networks in Nordic countries. Some are small but have high annual heat outputs due to regular use. Some are large and play a role in storing solar thermal heat from summer until it is most needed in the winter months.

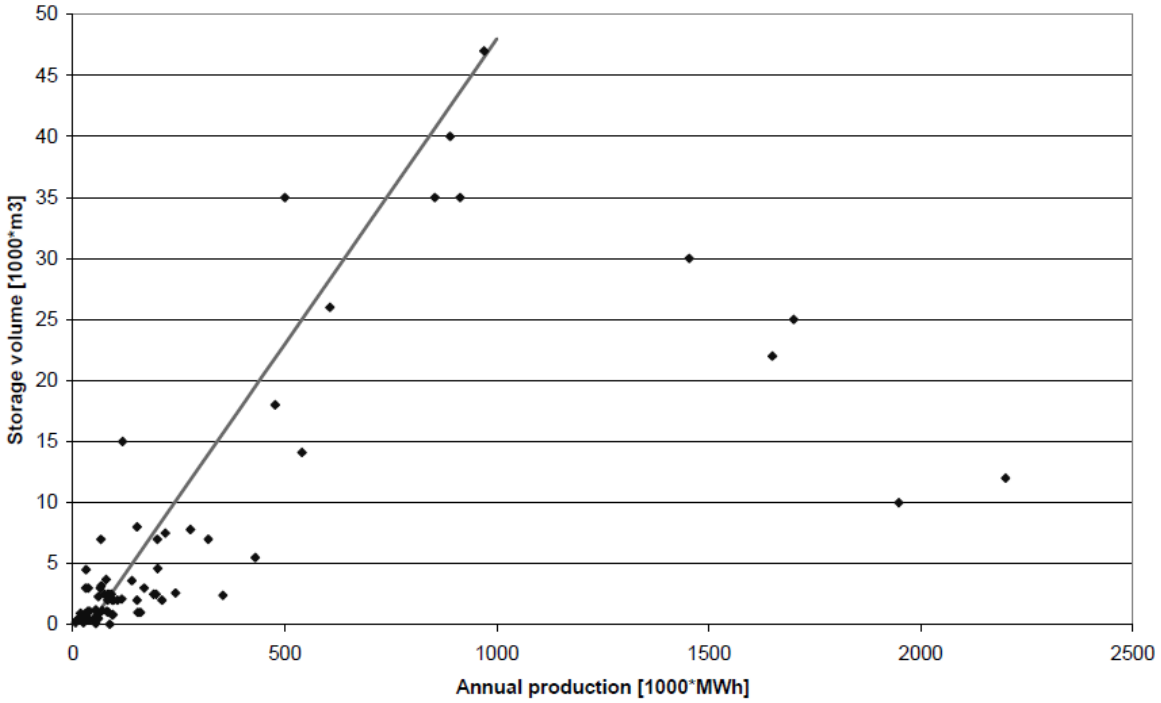

Figure 2-30: The dimensions and annual heat outputs from thermal stores in Nordic countries.
Source: IEA (2005b).

Table 2-7 lists some notable hot water store examples in Europe. A survey of UK DH systems found 12 heat stores in operation ranging from 30 to 950m^3, with one exception reported at 2300m^3 and a mean volume of around 200m^3 and median of 100m^3 (DECC, 2013n). This study has identified fourteen sites, mentioned in Table 2-8 and Table 2-9.

Table 2-7: Examples of hot water storage in European heat networks.

Location	Storage Capacity	Scale/Load	Notes	Reference(s)
Attenkirchen, Germany	500 m^3		Store for solar DH, store surrounded by boreholes. Performance data is limited.	IEA (2002), Reuss et al. (2006)
Avedorevaerket, Copenhagen	2x22,000 m^3		Allows flexibility to participate in Nord Pool electricity day-ahead spot market. There is also 24,000m^3 elsewhere on the DH system.	DONG Energy (n.d.), Elsman (2009)
Eggenstein – Leopoldshafen	4,500 m^3 pit 30m^3 tank	1600m^2 solar collectors, 2x600kW gas boilers		Eames et al (2014)
Gram	122,000m^3	44,000m^2 solar collector	5.3 MW_e engine, 29000MWh/yr demand 2x5MW gas boilers 10MW electric boiler, 900kW electric heat pump. 2000MWh/yr waste heat from industry.	Ramboll (2016).
Hamburg DH	4,000 m^3		Allows domestic-level solar thermal panels to store their hot water for long periods.	E.ON (2011)
Hannover, Germany	2,795 m^3		Store for 106 low energy houses with a solar-assisted DH system. 71% storage efficiency.	Raab et al. (2005)
Linköping	600 MWh		District heating store.	Rolfsman (2004)
Lyckebo	100,000 m^3		Rock cavern store to help with solar thermal integration.	IEA (2008)
Marstal, Denmark	75,000 m^3 pit	33,365m^2 solar collectors, 1.5MW heat pump, 4MW biomass boiler	Serves heat to 1500 members. Store costs €670,000 in 2003 prices. Average supply and return temperatures are low (74/36ºC).	Ellehauge and Pedersen (2007), Gong et al (2013), Eames et al. (2014)
Munich	5,700 m^3	1.4 MW absorption heat pump	300 apartments and a 2,900 m^2 solar thermal array.	Eames et al. (2014)
Neckarsulm	63,360 m^3 borehole	5,760 m^2 solar collectors	Supplies 300 apartments and has 538 boreholes.	Eames et al (2014).
Nuremberg	18 x 85m boreholes		Supply a three-storey office building of 1530m^2 area.	Eames et al (2014).
Rostock	20,000 m^3 aquifer	110kW heat pump	108 flats and a 980m^2 solar collector. 30m^3 buffer store.	Eames et al (2014).
Toftlund	80,000m^3	28,000MWh demand	3MW electrical boiler, 4.5MW gas boiler, absorption heat pump, 1500-4000MWh/yr waste heat from food plant.	Ramboll (2016)
Turin	3x800m^3		Plans are to add eighteen more stores.	Verda and Colella (2011), Fracastoro and Poggio (2012).
Vojens	200,000m^3 pit	70,000m^2 solar collector	3 gas engines, 10MW electric boiler, absorption heat pump, gas boilers	Ramboll (2016)

Table 2-8: Examples of non-univeristy heat networks and heat storage capacity (if present)

Location	Storage Capacity	Scale/Load	Annual CO_2 saving	Notes	Reference(s)
Barkantine	2 x 105 m^3	1.4MWe CHP, 2x1.4MW gas boilers	2,500	Serves 700 homes, a leisure centre, swimming pool and primary school.	Xergi (2013), Dalkia (2014).
Birmingham		7.5 MWe CHP 60,000MWh heat 4,900 MWh cold	14,000	Four energy centres, including 2000kW,1600kW,725kW CHPs	Engie (2016), Cofely (n.d.), Finning (2014).
Bunhill	115m^3	1.9MWe	2,000	Over 700 homes in phase 1.	Green Investment Bank (2015), Vital Energi (2016b).
Commonwealth Games Athletes' Village	70 m^3	844kWe CHP, 3x3MW gas boilers	2,093	Serves 704 homes, velodrome and a 120-bed care home. Approximately 60% savings.	Vital Energi (n.d.), City Leagacy (n.d.).
Coventry	650 m^3	9,000MWh (current) 73,000MWh (future)	1,500	95°C store, can be recharged in 4 hours.	CWLEP (2014)
Dunfermline	100m^3			Landfill gas and 2.4 MW gas boilers.	Scottish Futures Trust (2015). ADE (2015).
King's Cross	2 x 85m^3	3x2MWe CHP, 3x10MW boilers			Vital Energi (2016).
Leicester		4.8MWe CHP 58,000 MWh	8,400	City Centre; other schemes have 42,000 MWh, 0.163kgCO_2/kWh. 150kW biomass boiler. 2x1600kW CHP at University and 1600kW at St Marks.	Cofely (2012), Cofely (2014), Finning (2014)
Pimlico	2500 m^3	3.2MWe CHP, 3x8MW gas boilers.	11,000	District heating store power 3.4 MW_{th}. Capacity 18 MWh. 3200 homes and 50 commercial properties.	ERP (2011), Eames et al. (2014), City West Homes (n.d.)
Queen Elizabeth Olympic Park	27.5 MWh hot buffer	Up to 200MWth, 64MW cooling and 30MWe	11,700	Two energy centres. Growth to 100,000 MWh expected. 4 MW absorption chiller, 2x 7MW ammonia chillers (part time), 750m^3 cold buffer (4.7 MWh). 9.5MW CHP and 83.5MW boilers, 57MW cooling capacity	Cofely (n.d), Cofely GDF Suez (2013), GDF Suez (2015)
SELCHP, London	0		8,000	Energy from Waste CHP serving heat to 2700 properties.	Recycling & Waste World (2016)
Sheffield City Centre	0	100,000 MWh	21,000	Energy from Waste CHP serving 150 buildings. TERMIS software used to analyse heat storage. Supply temperature raised in hours before peak demand. Peak demand 41 MW	Vital Energi (2014), Veolia Environmental Services (2013b,2010)
Sheffield Lower Don Valley	0	30MWe 25MWth	80,000	Biomass CHP. 10 MW battery also present to provide frequency response for the UK grid.	Capula (2016), Wind Power Monthly (2016).
Southampton	0	70,000 MWh	11,000	2MW Geothermal well, 8 MW of CHP plant (incl 5.7MW CHP), 21.5MW peak thermal demand	Cofely (n.d.), Cofely (2012)
Thameswey, Milton Keynes	3 x 160 m^3	6MWe CHP, 14,000 MWhth, 16,000 MWhe	1,500	Includes 10MW gas boiler. Around 3000MWh/a heat for cooling.	Xergi (2013), Thameswey (n.d.), CODE (2010)
Walsall		4,900 MWhth 4,200 MWhe	613 out of 3,070 (20%)	Cofely feasibility study, 334kWe CHP produces 1,898 MWhe and 51% of the heat (2,551MWhth). 1.6 MWth peak	Cofely (n.d.)
Woking	163 m^3			District heating store. Power 1.6 MW_{th} Stores help balance 2x1.25 MW gas boilers and 2x400kW absorption cooling	ERP (2011), Xergi (2013),
Wyndford Estate, Glasgow	120m^3		Up to 7,000	1.2 MW gas CHP with three 4.5 MW backup/peaking gas boilers. 1800 homes. At current heat demands, there are 4058t emissions from gas use on site less a credit of 2624t for displaced elercricity meaning a saving of 2357t compared to the electric alternative of 3790t.	Scottish Futures Trust (2015), SSE (n.d.)

Table 2-9: Examples of heat networks, CHP and heat storage in UK universities.

Location	Storage Capacity	Scale/Load	Annual CO_2 saving	Notes	Reference(s)
Aston			4,400	Will link to Birmingham's heat network.	DECC (2014o)
Bradford		1.4MWe CHP	1,900	Cost savings of £400,000/year.	Cogenco (2013b)
East Anglia		3x1MWe/1.4MWth CHP 1MWth absorption chiller		0.1909 kg CO_2/kWh carbon intensity of heat.	InnovateUK (2014)
Edinburgh	100m^3	1.4MWe CHP 2x9MW boilers	1,016	Approximately £170,000 per year energy cost saving.	UKDEA (2016)
		526kWe CHP	450	£1,000,000 CESP project.	IDEA (2006)
		2.7MWe CHP 2x7.5MW boilers	2,600	Low-NOx gas boilers. £450,000 fuel cost saving. £4.3million capital expenditure (2003).	
	75m^3	1.6MWe CHP 15MW of boilers	1250	600kW absorption chiller, £7,000,000 installation costs and cost savings of around £500,000/year.	
Glasgow Caledonian		845kW CHP	750	£250,000 annual savings	Clarke Energy (2013b)
Lancaster	100m^3	1.9MWe and 2.2MWth CHP	2,800	20% of annual electricity consumption. Annual June-September shutdowns for network inspection and maintenance. Emission footprint approximately halved for electricity. Significant cost savings.	Lancaster City Council (2013), Lancaster University (2014).
Liverpool		2x2MWe +1x3.5MWe	7,000		University of Liverpool (2014). Vital Energi (2015).
Loughborough		500kWe	354	Commissioned 2007	Loughborough University (2014)
		1MWe/1.2MWth	1,000	15% of total campus electricity, commissioned 2008	
		1.6MWe/1.63MWth	2,250	Saves £340,000 per year, 25% of University electricity load	
Warwick	300m^3	400kWe+2x1350kWe +1350kWe	3,500	Saves £300,000 per year. Absorption chillers link to the dual 1350kW units with ice storage. Thermal store cost £320,000. 300 tonnes of storage at energy centres, 500m 300 tonnes of storage at energy centres, 500m^3 including all stores.	Cogenco (2013), Warwick University (2016b), Warwick University (2016c).

From Table 2-7, there is in total of at least 6150m^3 of heat storage on heat networks in the UK equivalent to approximately 150 MWh of energy storage; the capacity is dominated by large stores in Pimlico, the Olympic Park and Coventry.

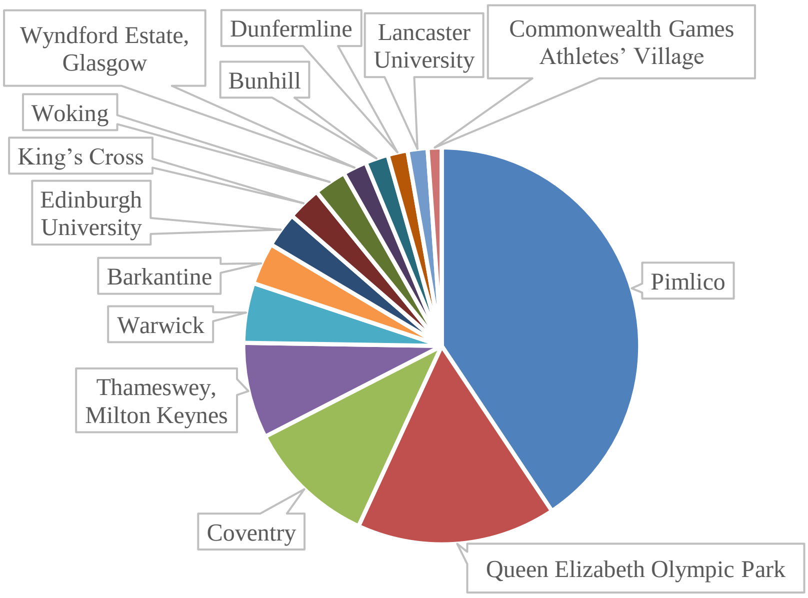

Figure 2-31: A pie chart showing the distribution of UK heat network heat storage by location.

Many of the European examples in Table 2-7 involve large pits or aquifers. The Lyckebo example, in Sweden, hosts a large cavern which was constructed in 1982 to hold excess hot water from solar thermal sources connected to DH, the design is shown in Figure 2-32 (IEA, 2008). Rock caverns have been used in Scandinavia quite widely during the cold war in order to store oil and ensure security of supply but these caverns are being phased out (IEA, 2008), but there are also more recent examples such as a 190,000m^3 cavern built in Finland in 1996 (IEA, 2005a).

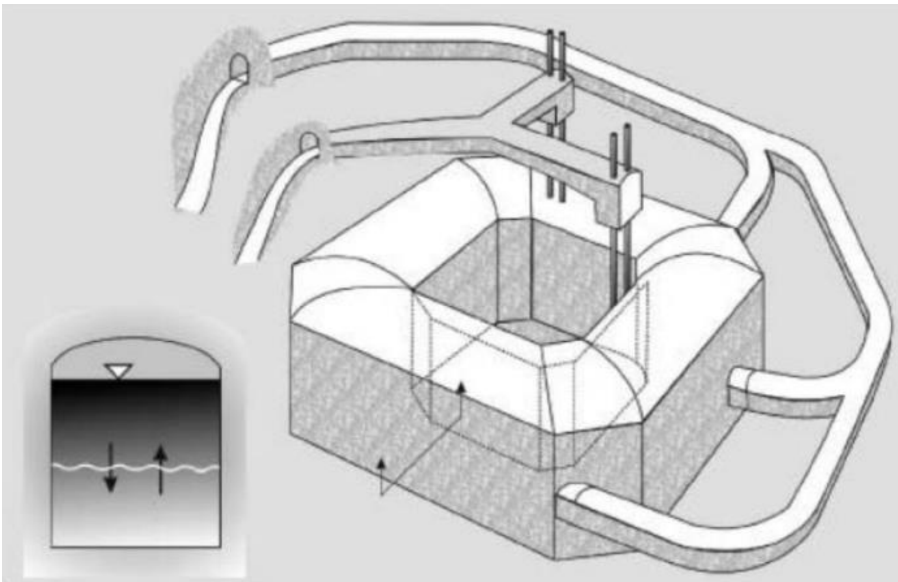

Figure 2-32: Layout of Lyckebo hot water cavern.
Source: IEA (2008).

Figure 2-33 shows how the temperature profile in the store changed during charge and discharge during its second year of operation. There is a clear stratification of hot upper layer from cold lower layer. As the store was charged, the hot upper layer thickened while during discharge that layer thinned out again. In its second year, 74% of the energy added to the store was recovered despite no thermal insulation being used (Duffie and Beckman, 1991).

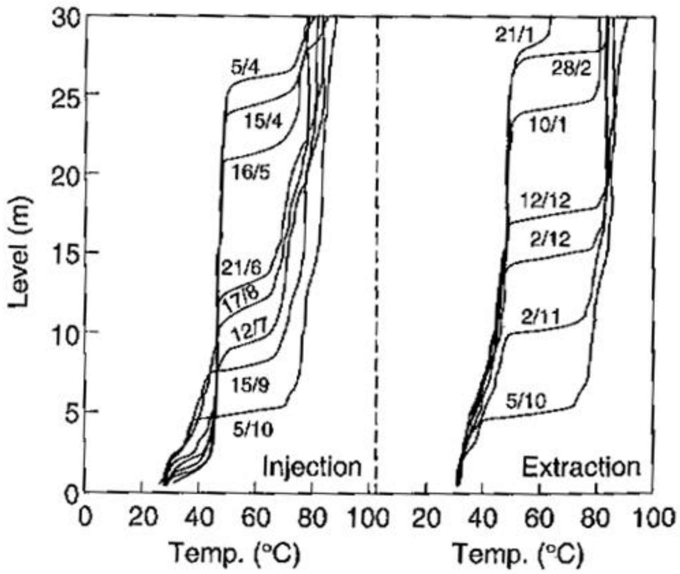

Figure 2-33: Variation of temperature profiles for Lyckebo store during charge and discharge.
Source: Duffie and Beckman (1991).

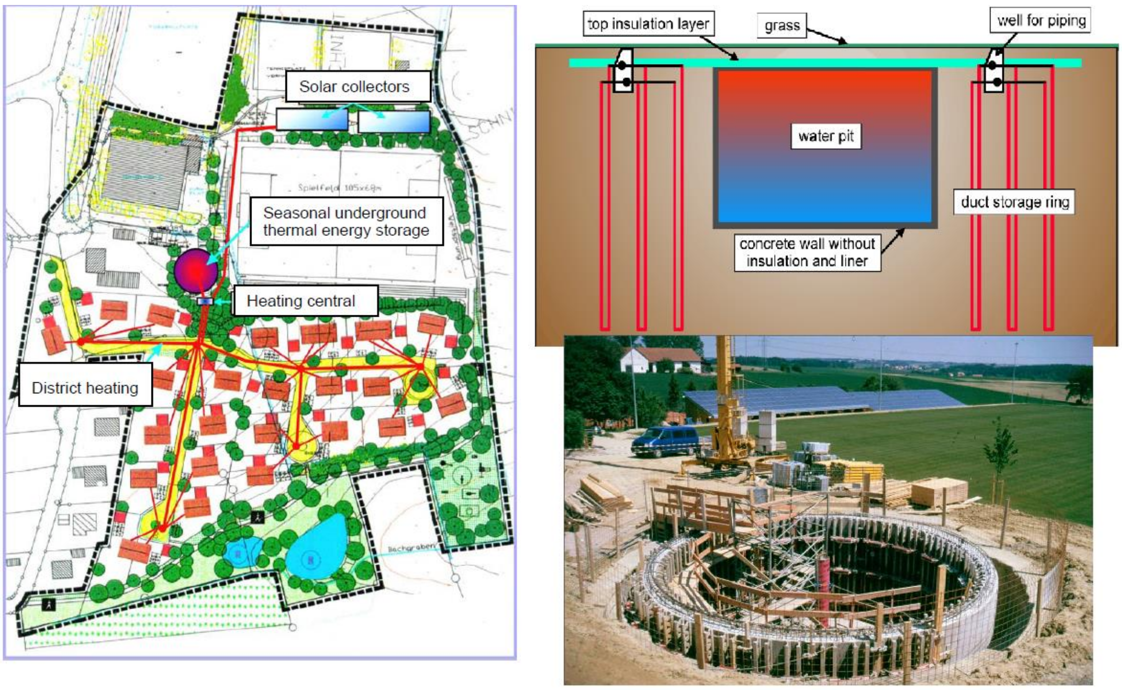

Figure 2-34: A water store concept with low insulation and surrounding borehole heat exchangers.
Sources: Reuss et al, (2006) and (ZAE, 2013).

Figure 2-34 shows a 500m^3 hot water system in Attenkirchen, Germany, which is surrounded by boreholes. During construction of the pit wall the borehole heat exchangers had to be moved away to 1.5 metres from the wall due to construction difficulties (IEA, 2002). This system found problems in terms of bad control system programming and lack of available submersible pumps that could handle water at 90°C (Reuss et al, 2006). A Sankey diagram for the scheme is reproduced in Figure 2-35.

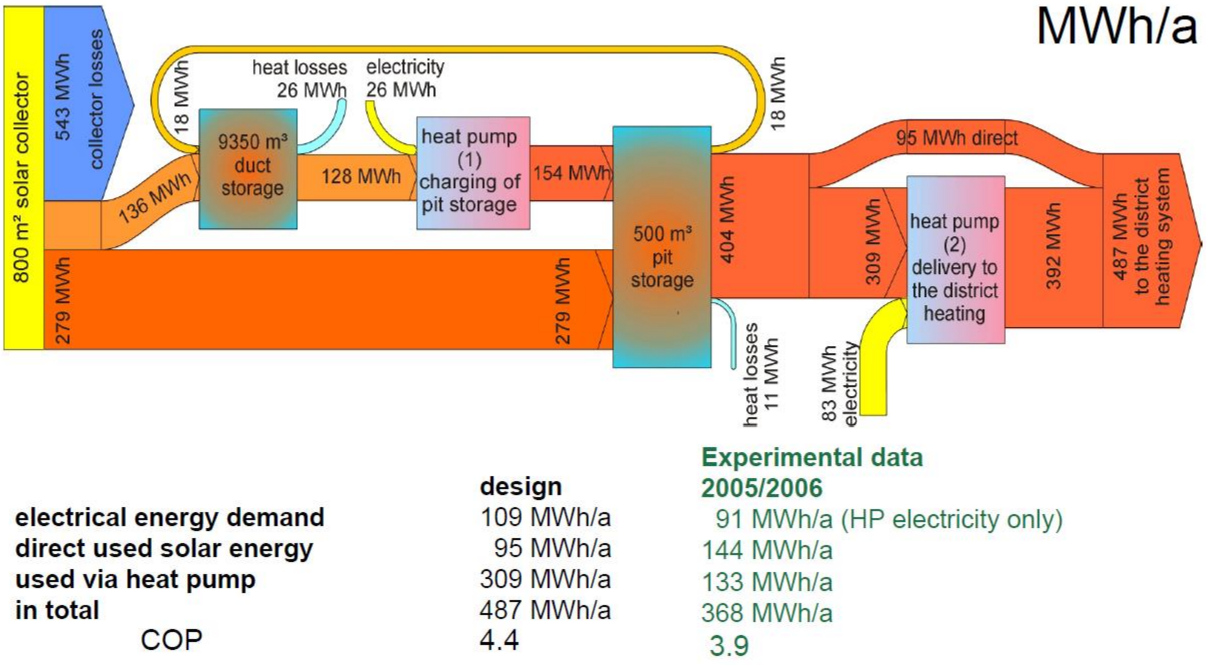

Figure 2-35: The design specification Sankey diagram and the actual performance for comparison.
Source: Schoelkopf (2006).

The largest pit thermal store has been operational since spring 2015 in Vojens, Denmark, for a solar DH system and holds 200,000 cubic metres (State of Green, 2016), shown in Figure 2-36.

Figure 2-36: Vojens 70,000m^2 solar thermal array and 200,000m^3 pit thermal store.
Source : State of Green (2016).

2.5.2 Latent Heat Storage

Material Choice

The choice of material will depend mainly upon the phase change temperature required. Cost, density, thermal expansion and chemical behaviour will also be important for systems to be practical and economic. A wide range of materials that have been investigated for phase change heat storage are also reviewed by Zalba et al (2003). Some candidate materials are shown in Table 2-10, with definitions of enthalpy changes defined in Section 3.1.1.

Table 2-10: Properties of some low and medium temperature phase change materials.
Source: Hauer (2013).

PCM	Melting Temperature (ºC)	Enthalpy of Fusion(kJ/kg)	Density (g/cm^3)
Ice	0	333	0.92
Sodium Acetate Trihydrate	58	250	1.3
Paraffin	-5 to 120	150 – 240	0.77
Erythritol	118	340	1.3

Most PCMs work at low temperatures, particularly the organic ones. Inorganic salts undergo melting phase change at high temperatures, with relatively high amounts of energy absorbed. Organic molecules will mostly be less corrosive but may be problematic in terms of flammability.

Pumpable Phase Change Materials

Water-ice slurries, where solid ice is crushed and added to a circulating fluid that can be pumped to provide cooling to buildings on a pipe network, are described in (Hauer et al., 2010). A non-water PCM could be added to a heat transfer fluid for a district heating system by microencapsulation, emulsification or by attaching to the PCM to a substance that will remain suspended. The expense means that application of pumpable phase change materials is likely to be on small scales, for example in air conditioner systems rather than district heating where the sheer volume needed may make the cost prohibitive. A phase change slurry is used for the air conditioning systems at Narita Airport in Tokyo (Hauer et al, 2010).

Micro-encapsulation of PCMs

Small particles of PCM can be encased in an unreactive material in order to be added to a fluid which carries them and increase its heat capacity (Jin et al, 2010). Micro-encapsulated particles could release heat by undergoing phase change when the temperature of the surrounding water falls below the desired temperature.

Such technology could be applied to existing district heating schemes where water is circulating continuously provided they do not accumulate in bends or filtering systems. These microcapsules are already manufactured so that they can be mixed into some building materials. Rau et al. (2012) investigate the behaviour of the microencapsulated PCMs during their formation.

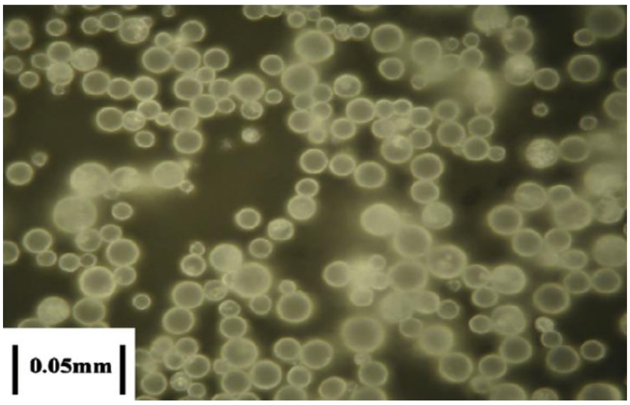

Figure 2-37: Optical phase-contrast micrographs of PCM capsules.
Source: Zhang and Zhao (2011). Notes: These capsules were made by Ciba Speciality Chemicals (UK), from paraffin wax with a cross-linked acrylic polymer shell.

Zhang and Zhao (2011) researched the properties of microencapsulated PCMs like those shown in Figure 2-37, noting the need for surfactants (around 1% by weight) in the heat transfer fluid. They found that in smaller capsules, the lower number of nucleation points meant that the PCM could undergo supercooling. Hence the range of capsule sizes present will affect the recrystallisation process and allow multiple phase transition temperatures, whereas for the melting process there is only one temperature for the transition.

So with microencapsulation, the range of particle sizes to be used as well as the PCM material itself will be important characteristics. Surfactants can help lower drag (Hauer et al, 2010) and particles in suspension will likely alter the pumping characteristics of the fluid. The mechanical properties of micro-encapsulated PCMs are important since the break-down of capsules leads to degradation; this was studied by Giro-Paloma et al. (2012). Goel et al. (1994) studied the heat transfer properties of microencapsulated phase change materials, concluding that the particle diameter to pipe diameter ratio has important effect in a heat exchanger.

Microcapsule paraffin slurries reach heat capacities of 85kJ/kg in a 60% water mixture by weight, compared with 230kJ/kg for paraffin bulk melting. But these levels of microcapsules were seen to mean high viscosities and keeping the fraction of capsules below 25% when using temperatures lower than 25°C was deemed sensible. Too high a concentration of microcapsules may cause particles to clump together leading to fall in heat transfer rates if the capsule clumps then sediment out of suspension.

Vorbeck et al. (2012) tested a 5m^3 phase change slurry unit with microencapsulated paraffin. Their tests showed that the heat storage capacity was nearly double that of the same volume of water but that the energy used for pumping through the heat exchanger was five times as much per unit volume pumped, or 2.5 times as much per unit of energy absorbed.

Emulsions

Emulsions, where the PCM is mixing as a liquid, function well up to 50% paraffin and have acceptable viscosity hence giving higher storage potentials of up to 120 kJ/kg (Hauer et al, 2010). Where fluid PCM droplets mix with fluid, the surface tension of water tends to lead to fluid separation. Emulsifiers are chemicals deployed to reduce the surface tensions and make the suspension more stable. When the PCM is molten the viscosity of the fluid is low, but when the PCM solidifies the viscosity increases to levels similar to the microencapsulated samples. This is a complex change that may prove hard to manage in real life systems.

Case Study: Erythritol

Agyenim et al (2009) model the energy storage capability of erythritol which changes phase at 118°C, which may be of interest for high-temperature district heating systems which traditionally operate at 110-120°C. This provides a low-pressure alternative to storing the district heating water itself which required the use of pressure vessels; also the fact that Erythritol is a common food additive means that it is already manufactured on a large scale at relatively low cost.

Agyenim et al (2009) used a charging fluid at 140°C and this was supplied at 30 kg per minute. The use of radial fins in the cylinder led to the fastest melting rate but it took around eight hours to melt the relatively small sample. Agyenim et al. (2011) investigated the potential for using erythritol for capturing heat from a solar collector and rejecting it at a high enough temperature for running an absorption chiller at around 80°C. Temperatures of the HTF during charging needed to be 140°C to achieve full melting with an average temperature of 126°C in the phase change material by the time it had completely melted, whilst during discharge the average HTF temperature was 80°C (*ibid.*). Silicone coatings are often used to contain phase change material but these were found to be permeable to the sugar alcohol erythritol (IEA, 2013).

Overall, the temperature differences necessary to overcome low conductivity and to encourage convection in the phase change material lead to a big difference between the temperature of the heat transfer fluid during charging and during discharging.

2.5.3 Thermochemical Storage

Thermal Dehydrogenation of Alcohols

Heat can be used to decompose alcohols into aldehydes and hydrogen as in Equation 2.5. The forward and backward reactions are undertaken at different temperatures and allow the thermal upgrading of heat, but there are significant heat losses to account for.

$$\text{Alcohol} \leftrightarrow \text{Aldehyde (or ketone)} + \text{Hydrogen} \qquad (2.5)$$

For isopropanol, there is a cycle as in Equations 2.6 to 2.8.

$$(CH_3)_2CHOH_{(l)} \rightarrow (CH_3)_2CO_{(g)} + H_{2(g)} \qquad \text{at 80-90°C} \qquad \Delta H = +100.4 \text{ kJ/mol} \qquad (2.6)$$

$$(CH_3)_2CO_{(g)} + H_{2(g)} \rightarrow (CH_3)_2CHOH_{(g)} \qquad \text{at 150-210°C} \qquad \Delta H = -55.0 \text{ kJ/mol} \qquad (2.7)$$

$$(CH_3)_2CHOH_{(g)} \rightarrow (CH_3)_2CHOH_{(l)} \qquad (2.8)$$

In the isopropanol example, heat can be absorbed at low temperature in the first reaction and emitted at a higher temperature in the gas phase reaction. However, less energy is released at the high temperature reaction and the remaining energy is released when the alcohol recondenses into the solution in the third step of the cycle above. Aldehyde (or ketone) concentrations need to be kept low during the dehydrogenation reaction in order for decent rates of reaction to occur. Aldehydes or ketones can be vaporised from the solution but their concentration significantly limits the rate of heat absorption (Gastauer and Kameyama, 1995).

2.6 Low Temperature Store Technology (<60°C)

2.6.1 Hot and Cold Water Storage

Solar ponds

An interesting idea where hot water is kept insulated deep in a pond by having high salinity and therefore density. Lower-salinity layers near the surface act as insulation (Pinel et al, 2011). On the other hand, salinity of water can add to the corrosion rate of pipe work used for heat exchangers or moving fluids. Solar ponds can reach up to 95°C such as a solar pond in El Paso that powered a 100kWe organic Rankine cycle (Hasnain, 1998).

Aquifers

Subterranean aquifers that hold groundwater can be used as hot (or cold) storage by drilling two holes some distance apart, heating (or cooling) ground water from one well and pumping into the other. This results in a temperature differential between the wells. Then when heat is to be released, extract water from the hot well, absorb the heat, and return that groundwater to the cooler well. Typically, round-trip energy efficiencies for charging and discharging are around 70% (Dincer et al., 1997). Rosen (1999) calculates round-trip exergy efficiencies, which seems more indicative of performance since heat may be recovered at too low a temperature for use for building heating but the energy content is still counted.

With this technology it is important to be aware of practical problems possible from lime scale build-up. Fouling corrosion of the pipes and equipment is more likely for these systems than for the closed-loop systems that do not allow the heat transfer fluid out of the pipes (Yang et al., 2010). There are advantages in that the system only needs a small amount of pipe work to achieve quite a high storage capacity so this is good technology for large heat stores. Temperatures used are typically 40-50°C, but losses rise at higher temperatures. Heat can be stored at around 100°C but the boreholes need to be deeper and are therefore more expensive to drill.

Aquifer technology has been used to supply heating and cooling to Stockholm Arlanda Airport since 2009 (Swedavia.com, 2012). The aquifer is expected to reduce the airport’s annual electricity demand by 4GWh and reduce the energy taken from DH by 15GWh (*ibid.*). The potential for an aquifer in Rostock, Germany was thoroughly analysed before construction to assess geology, circulation characteristics, and pumping characteristics (Schmidt et al., 2000). After years of use, the aquifer was found to have mean volumetric heat capacity of 2.7MJ/m^{3}K and conductivity 3.2 W/mK (Schmidt and Müller-Steinhagen, 2004). Pressurised nitrogen has been used with this system in order to prevent oxygen getting into the well and causing mineral precipitation and clogging of the well (*ibid.*).

Problems of thermal interference of aquifer boreholes have been experienced where multiple users have been using the same aquifer system, the risks being higher when the sites are close together. Environmental regulations apply in the UK controlling how much water can be taken from the ground as well as how much water can be pumped into the ground at one temperature. The Environment Agency’s experience of regulating the open-loop ground source heat pumps in London, used primarily for cooling, is discussed by Fry (2009). There are risks associated with geology, the water may move in unexpected ways as underground systems are hard to monitor, compromising the storage system. The role of borehole thermal stores for cleaning contaminated ground has been discussed by Slenders et al. (2011); however the increased mobility of arsenic in groundwater can be a cause for concern if drinking water is extracted nearby (Bonte et al., 2013).

Cold Storage

Cold water storage for chilling systems can help to avoid electricity use at peak-price times. Ice stores can help to manage the air conditioning systems, in some cases saving almost 10% of energy use and CO_2 emissions (Sanaye and Shirazi, 2013). Khan et al. (2004) state that multiple-tank cold water storage is the best option to minimise the mixing of cool water with the warm water returning from a building cooling system. Bo et al. (1999) explored the use of phase change materials (PCMs) for cool storage in district cooling systems, considering a selection of paraffins. They note that laboratory grade paraffins with a distinct melting point are expensive, but that they show better performance over many cycles.

2.6.2 Rock Bed and Ground Systems

Rock is a generally low-cost material that can be raised to higher temperatures than water. Rock beds also stratify by having different temperatures in different parts but without buoyancy-induced mixing. Low specific heat capacities mean that three times the volume of rock is required to store the same energy as water (Dincer and Rosen, 2002).

Using air as a heat transfer fluid is one option, and air can carry heat in at temperatures well over 100°C but the gaps necessary within the rocks to allow heat transfer reduce the heat capacity per unit volume. Better heat capacities occur when water is used as water sitting amongst the rock increases the heat capacity. However, having water amongst the rocks raises conductivity and keeps the amount of stratification low and temperatures over 100°C would require pressurisation of the system to prevent the water from boiling and the pressurised casing for the store would add cost.

Rock-Air Systems

When the bed is fully charged it reaches the temperature of the heat transfer fluid. The finite heat transfer coefficient smears the steps in temperature when the unit is being charged and discharged. Figure 2-38 shows the variation of rock bed temperature over time for a heat store trialled by the University of Colorado with solar-supplied heat (Duffie and Beckman, 1991). Note how the inlet temperature from a solar thermal source varies through the day, air flowing upward in the store at night collects heat, entering the system at around 20°C.

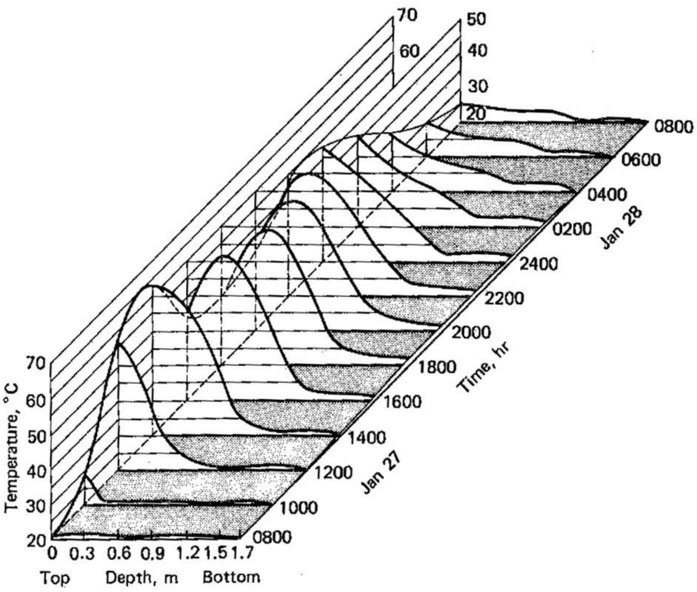

Figure 2-38: Changing temperature profile over time in an operating air-fed rock heat store.
Source: Karaki et al. (1977).

Water-gravel systems

Water-gravel systems work on a similar principle to water stores but to store the same amount of energy the volume has to rise by around 50%. However, no load-bearing frame at the sides or on the lid is needed as the gravel counters those forces (Schmidt et al., 2004). Repairing leakage would be more difficult than with a water-only tank (Ochs et al., 2008). Shallow systems tend to handle lower temperatures (20-50ºC) while deeper systems are suitable for temperatures of 60-90°C (IEA, 2008). Researchers at the University of Stuttgart were looking to install a hot water storage tank to help regulate their heating systems, but important underground waterways meant that construction of their ideal adiabatic concrete tank would have been difficult and expensive; the space needed for constructing the concrete walls would also have reduced capacity significantly (Hahne, 2000). The adopted solution is shown in Figure 2-39 and incorporated a water-gravel system.

The Stuttgart store took six months to build and the cost was approximately 300,000DM (excluding VAT) (Hahne, 2000). Trials found that heat inputs were high on sunny days in winter when the storage was cool and there was a significant difference between the store temperature and the temperature of water coming from the solar collectors (around 35°C).

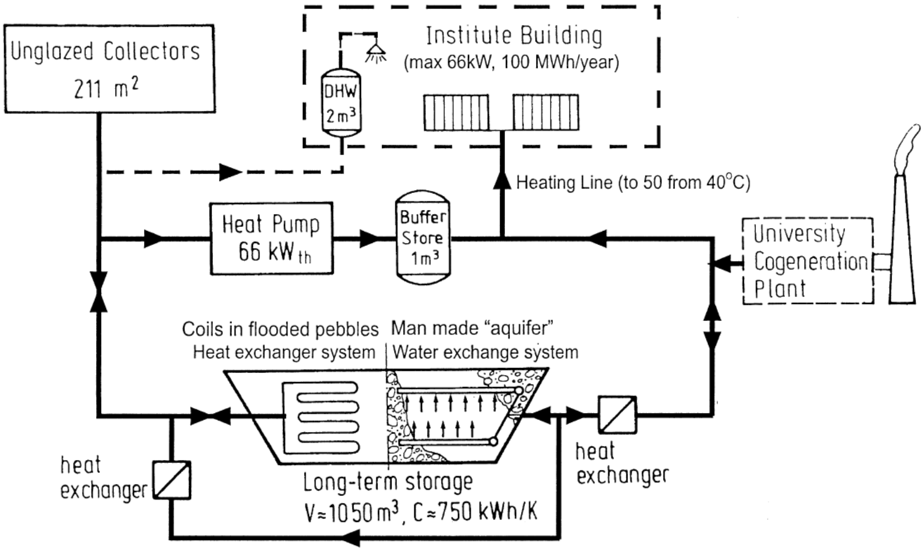

Figure 2-39: A schematic of the heat system at ITW, University of Stuttgart.
Source: Hahne (2000).

The structure of the store, with three layers of gravel and pebbles, was designed to create different flow resistances at different depths. Details of the layout of the water distributors/collectors and incorporated heat exchanger system are given in (Hahne, 2000). High solar thermal output in summer meant around 40% of this heat penetrated into the surrounding ground. However, this loss was not permanent with around half of that heat re-entering the store in winter when its temperature fell. Hence the storage capacity of the system actually includes heat storage in external ground (*ibid.*). Later experimentation at the Stuttgart site used the pit as an ice store to provide cooling in the summer. When used to store heat, elevated temperatures in the soil occur within a few metres of the tank but these tank temperatures will be low for a large part of winter, and the researchers concluded the effects on hibernating animals would not be significant (Hahne, 2000). The effective round-trip heat storage efficiency was around 80%; with the remainder lost permanently to ground; recalling that around half of the heat passing through the tank walls to the surrounding ground is recovered.

Duct Heat Stores

Boreholes can be used to access the thermal capacity of the ground up to depths of hundreds of metres providing opportunity for long term heat storage. A heat pump is likely to be required since the store will be at lower temperature than the required heat. The feasibility of such schemes depends upon the geology and environmental permitting requirement, in particular the avoidance of groundwater movement which carries the heat away.

For large seasonal stores the charge rate will be low relative to the capacity. At the Drake Landing Solar Community in Canada, it is found that the solar thermal panels deliver heat at around double the rate at which the borehole thermal storage can accept the heat and a short term hot water buffer allows the borehole charging to continue during the night (DLSC, 2014a). For boreholes, heat recovery rates of

50-60% on an annual cycle was seen in an example of heat recovery from a steelworks in Lulea (Rehau and NeoEnergy, 2013).

The volume of ground needed to store the heat is between three and five times the volume needed for an equivalent capacity hot water tank. The key performance indicator is called the specific performance, equal to the heat extraction rate in watts per metre of borehole depth (Hepbasli, 2005). Between 12 and 16 metres of borehole is typical for each kilowatt of thermal capacity (*ibid.*).

Ground heat exchangers usually use the circulation of pure water or a solution of antifreeze to carry heat through high-density polyethylene (HDPE) pipes. Horizontal systems are usually buried 1-2m underground (Yang et al., 2010) and need quite a large surface area for access during construction. Vertical borehole systems work well since the ground is near-constant temperature below around 10 metres depth (Sanner et al., 2003). Usually holes are drilled to be 10-15cm diameter and to a depth of 50-100m (IEA, 2008). It is important, however, not to oversize the boreholes since costs rise fast with depth and so the required heating demand must be carefully considered; extra boreholes can be added later to increase capacity.

Figure 2-40 shows how neighbouring boreholes affect each other, hence boreholes are spaced a few metres apart to gain access to more heat capacity. The bores can be connected in parallel or in series (usually with a radial arrangement). In the radial series arrangement, hot water entering the system is directed to the central holes first and then to the outer ones as temperature falls; the water travels in the opposite direction to regain this heat (*ibid.*). Figure 2-41 shows the borehole arrangement in Drake Landing Solar community in a grid with 2.25 metres between them. After a few years of operation the centre of the borehole field is expected to reach nearly 80°C (Dlsc.ca, 2013).

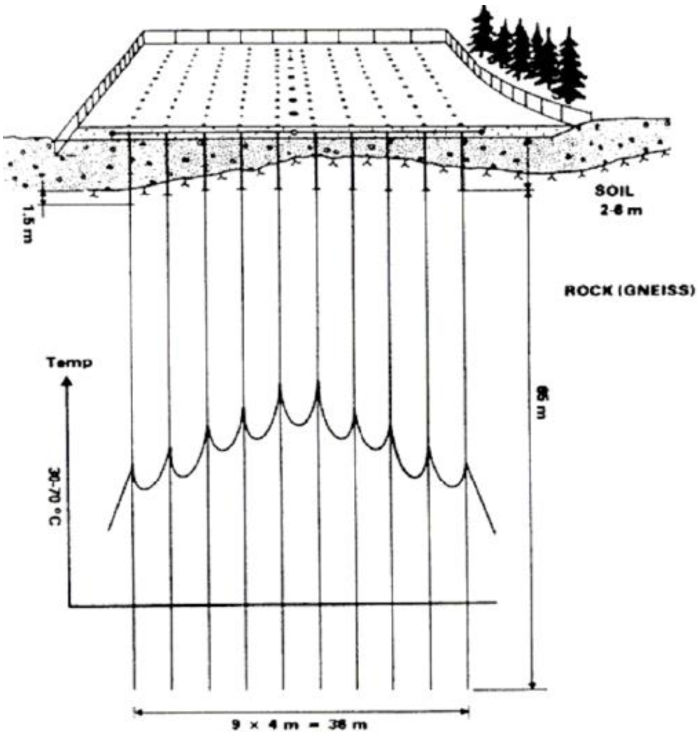

Figure 2-40: Underground temperature variation in a borehole field.
Source: IEA (2008).

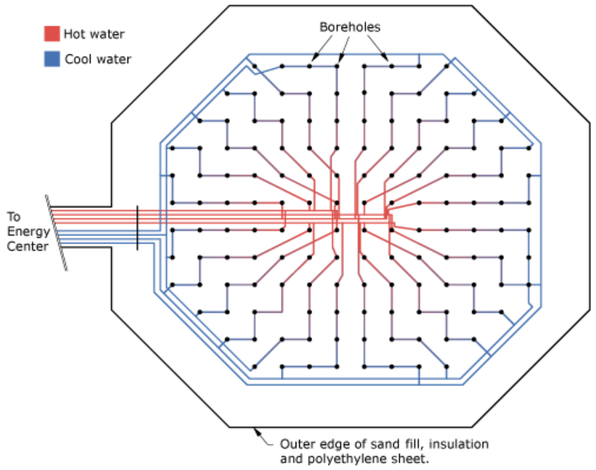

Figure 2-41: Borehole arrangement at the Drake Landing Solar Community.
Source: dlsc.ca (2013).

Wet ground can hold more energy and conduct better than dry ground, but interaction with the water table should be minimised as heat may be carried away by movements of water (Pinel et al, 2011). Gehlin and Hellström (2003) model the effects of water flow through fissures in broken hard rock near the borehole.

2.6.3 Heated air and building thermal mass

In the end, it is the temperature of air in the buildings and hot water delivered by DH that is the important outcome. Adjust timing of space heating operation and use the thermal inertia of buildings in order to maintain comfort is an option. Rolfsman (2004) estimated the potential for varying the indoor temperatures to store heat energy as 0.025 kWh/°C.m^2. Kensby et al. (2015) investigated the possibility for storing heat in the connected buildings by heating the air above the requirement and allowing the air to cool below the required temperature depending on balance of supply and demand. They noted that raised temperatures in the building heating system can take from around 30 minutes to an hour to propagate around a building. Ingvarson and Werner (2008) carried out experiments on varying the 'outdoor temperature' signal for buildings, finding that the storage capacity could be of the order 1000 MWh for a very large DH system such as the one in Gothenburg but the suitable variations of indoor temperature according to occupant experience remain unclear.

2.6.4 Latent Heat Storage

A range of candidate phase change materials are shown in Figure 2-42 and Figure 2-43. Bo et al. (1999) show how the temperature of phase change could be altered by varying the ratio of two alkanes (with differing chain length) in a paraffin mixture, achieving freezing points in the range 2 to 18°C with the same two alkanes, as shown in Figure 2-44; the enthalpy change of fusion was significantly less for a mixture of alkanes than for pure samples of either (*ibid.*).

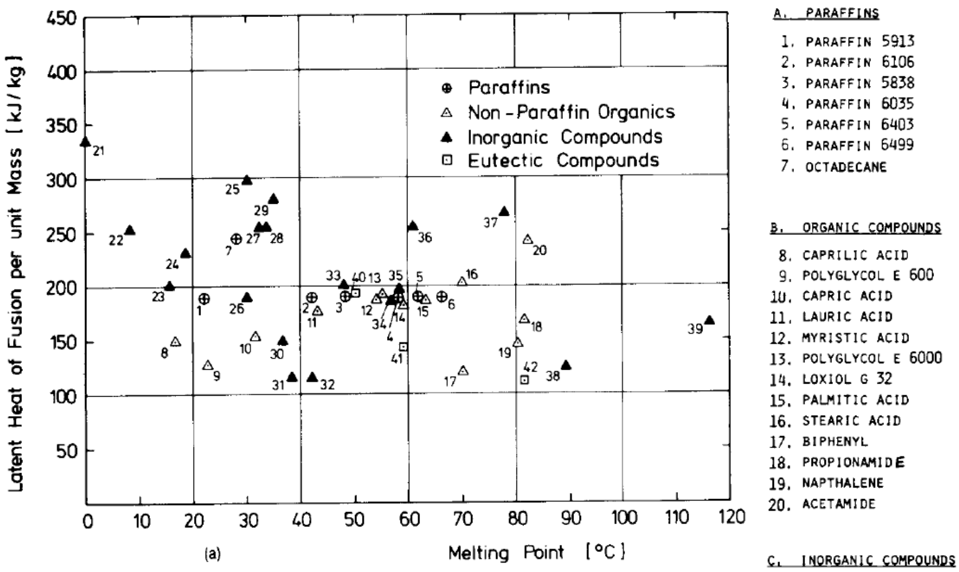

Figure 2-42: Phase Change Material melting points versus latent heat per unit mass. Source: Abhat (1983).

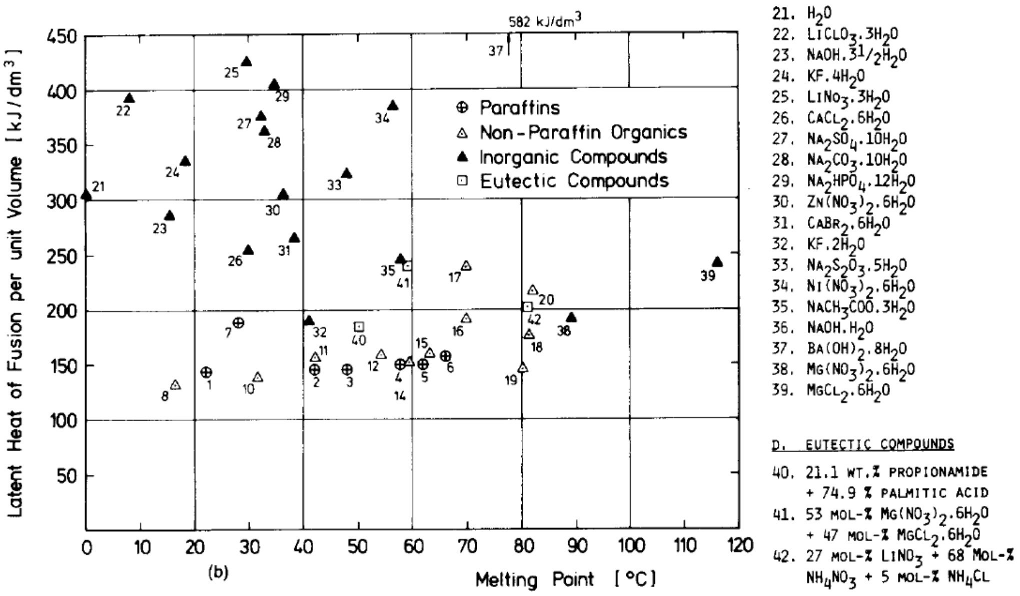

Figure 2-43: Phase Change Material melting points versus latent heat per unit volume.
Source: Abhat (1983).

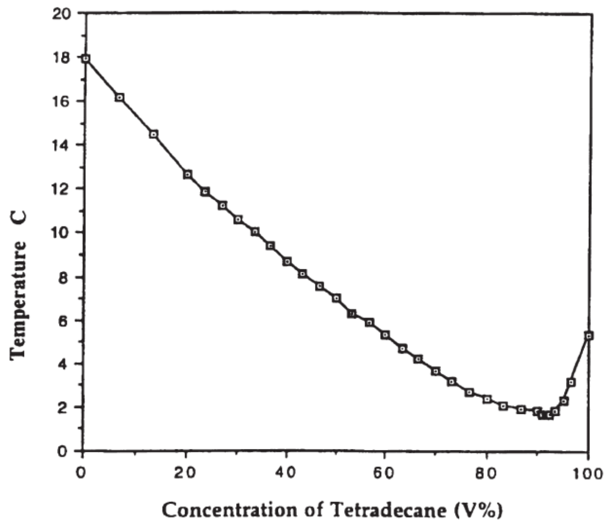

Figure 2-44: The variation in freezing point of a binary mixture of hexadecane and tetradecane according to composition.
Source: Bo et al. (1999).

Experimental Experience

Few phase change materials have been commercialised, there are sometimes uncertainties over corrosion or with degradation of the material over many melt-freeze cycles. The thermal conductivity for PCM can be poor and the crystallisation of the PCM onto the surface conducting heat away can often reduce the thermal conductivity hampering further heat extraction. This problem can be resolved by having a honeycomb structure through which the heat transfer fluid can pass, mixing in thermally conductive materials, or by encapsulating the PCM into small volumes which the fluid can pass around giving a high contact area in either case. Experimental work on PCMs are detailed in Table 2-11.

Abhat (1983) found that the geometry of the container has a significant effect upon the phase change behaviour of salt hydrates, with a large glass contact area promoting nucleation and limiting supercooling. A high surface area metallic heat exchanger kept the amount of supercooling very low. Abhat (1983) also showed that salt hydrates in open systems (i.e. those exposed to atmosphere) quickly degraded with cycling and so should be used in closed systems, and that some salts chemically react with some metals, stainless steel showing least corrosion but mild steel still performing fairly well.

Watanaba and Kanzawa (1995) describe the advantages of a PCM system where the melting point of the PCM is varied along the direction of travel for the heat transfer fluid. This helps to maintain the temperature difference necessary for heat transfer and results in faster melting even if the average melting point of the PCM is the same. Watanaba and Kanzawa showed through exergy analysis that graded melting points could significantly improve exergy efficiency.

Table 2-11: Experimental work on phase change materials.

Reference	Material(s)	Property investigated	Notes
Alkan and Sari (2008)	Fatty acids in PMMA polymer blends	Thermal and latent heat properties	These are "form stable" PCMs which are held in place by the polymer and do not need to be encapsulated.
Sari (2003)	Fatty acids	Performance after many cycles	Latent heat reductions of up to 28%, changes of melting temperature up to 8^{o}C after 1200 cycles.
Sari and Kaygusuz (2003)	Fatty acids	Performance after cycling, and corrosion on metal containers	Notably better performance with stainless steels and aluminium compared with carbon steel and copper.
Li et al. (2013)	Stearic acid	Enhancing thermal conductivity and shape stability with graphene oxide layers	Novel material was produced.
Mehrali et al. (2013)	Paraffins	Enhancing thermal conductivity and stability with graphene oxide layers	Higher thermal conductivities achieved, and stability over thousands of melt-freeze cycles.
Desgrosseilleurs et al. (2013)	Dodecanoic (lauric) acid	Performance after multiple cycles of industrial grade purity samples	The acids with melting point around 40^{o}C was cycled 500 times without significant degradation.
Velraj et al. (1999)	Paraffin	Enhancing thermal conductivity	Fin and Lessing rings (loops of metal ribbon with a central spoke) were found to significantly enhance conductivity, whilst steam-forming bubbles were not.
Cabeza et al. (2002)	Water/ice	Conductivity enhancement	The use of a highly conductive metal like copper is better than with stainless steel. Using a graphite matrix is even better than the metals
Sari and Karaipelki (2007)	Paraffin	Conductivity enhancement using expanded graphite	Significant conductivity increase and the latent heat is similar to that expected for each unit of PCM used.
Warzoha et al. (2013)	Paraffin	Conductivity enhancement with graphite foam	Particular attention paid to the degree of filling in paraffin amongst the foam structure.
Bugaje (1997)	Paraffin	Conductivity enhancement using aluminium sheet metal and expanded aluminium	The aluminium sheet fins worked better due to good contact with the outside tube of the container. Heat was entering through the middle.
Mettawee and Assassa (2007)	Paraffin	Enhancing conductivity by embedding aluminium powder	Much faster charging was seen and better efficiencies for solar thermal collector linked to it.
Stritih (2004)	Paraffin	Enhancing conductivity with steel fins	Fins helped but having too many was counterproductive due to inhibition of convection.

Applications

Farid and Kong (2001) experimented with placing encapsulated PCMs in a concrete floor alongside under floor heating in order to make best use of off-peak heating. Products based on room-temperature phase changes have been developed for use with building materials. For example, PCMs are used for temperature control in ceiling tiles in DECC's Whitehall office (AEA, 2011).

Okamoto (2013) described the use of ice storage in combination with a sea-water heat pump for cooling, resulting in energy savings and CO_2 emissions reductions; the electricity used for the heat pump operation was shifted into the night-time by use of the storage.

LaTherm have commercialised a transportable PCM unit, see Figure 2-45 and specifications in , for use in the German market to connect heat sources and demand (LaTherm, 2012).

Table 2-12: Specifications for sodium acetate portable phase change module.
Source: LaTherm (2012).

Unit total mass (excl. chassis)	29 t
Energy stored / unit	2.5 MWh
Typical charging power (90/65ºC)	250 kW
Typical discharging power (48/38ºC)	125 kW
Energy losses per day	<0.5%

Figure 2-45: A transportable trailer PCM thermal store.
Source: LaTherm (2012).

2.6.5 Absorption and Adsorption

Absorption processes are where a fluid flows into and amongst a host material forming bonds and altering the internal energy of the system causing heat to be absorbed or given off. Adsorption is a similar process but the contact happens only at the surfaces, usually of a solid, rather than throughout the bulk of the material. Table 2-13 lists sorption pairs for such reactions and the associated energy stored by the reactions.

Table 2-13: Important Sorption Storage Reactions
Source: Pinel et al. (2011).
Note: Energy density per mass refers to the total mass of all reactants involved. 1GJ = 278 kWh.

Absorption		Adsorption		Solid-gas reaction	
NH_3-H_2O	0.40 GJ/kg	H_2O-zeolite	0.08 GJ/kg	H_2O-Na_2S	1.27 GJ/kg
H_2O-NaOH	1.00 GJ/kg	H_2O-silica gel	0.14 GJ/kg	H_2O-$MgCl_2$	0.84 GJ/kg
				H_2O-$CaCl_2$	0.98 GJ/kg
				H_2O-LiCl	0.71 GJ/kg

Salt corrosion of the containment vessel generally gives absorption systems shorter lifetimes than adsorption ones; the absorbent should be changed every 4-5 years (Chan and Russell, 2011). Lithium bromide cannot accept waste heat at too low a temperature due to crystallisation problems, whereas silica gel – water, active carbon – methanol and charcoal – methanol sorption pairings can all function below 100°C and accept waste heat (Saha et al., 2003).

Reactions using water as the sorbent can be open to the environment since liquid water or steam, provided it is clean, can enter and leave the system. This is in contrast to most other chemicals which need to be contained. An advantage here is that liquid-gas phase changes can be allowed without having to store the evaporated volume of steam. Steam leaving the system will however carry the heat of condensation with it meaning an energy loss, unless a condensing arrangement is possible. There is added convenience from this for transportable stores since the weight of water does not need to be transported when the salts are dry, the container must however have the capacity to carry the extra mass of water on the return leg to the heat source when the salt is hydrated.

Biomass drying is an example of a dehydration reaction and is necessary for paper production. The new biomass power station in Sheffield could in theory benefit from the use of drying by increasing the boiler efficiency, but the waste wood feedstock is already low moisture content at around 20% (E.ON UK, 2014), and further handling and storage could be costly. If in future the operators wish to use a higher moisture feedstock such as forestry products then there may be enhanced opportunity.

Closed stores can require expensive heat exchangers for heat transfer. A closed, silica-water adsorption store for domestic-scale solar storage was developed in the MODESTORE project (Wagner et al., 2006). There were problems in that the necessary temperature lift of the HTF during adsorption was only achieved over 35% of the store's capacity, approximately 50kWh/m^3 for the pilot store (Mette et al., 2012). A schematic of this design is shown in Figure 2-46.

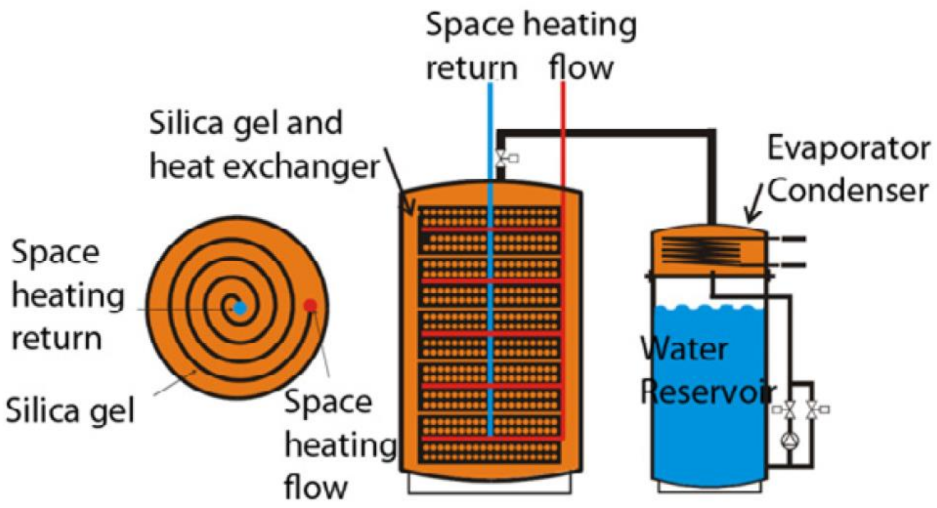

Figure 2-46: Schematic of the MODESTORE silica adsorption heat store.
Source: Mette et al. (2012), adapted from Wagner et al. (2006).

Experimental Experience

Abhat (1983) notes that irreversible precipitation phenomena occurs with most salt hydrates, which cannot be mitigated by stirring since hydrate binds to the outside of the anhydrous precipitate and hence very slow solid diffusion is the only mechanism for returning to the original state. Abhat also states that the poor nucleating properties of salt hydrates often leads to supercooling of the solution, which can be countered by using rough container surfaces or nucleating agents with similar crystal structures.

A practical set up for dehydration reaction with a rolling cylinder containment was explored by Herrick (1982), who found that all of the latent heat was recoverable with discharge rates of 313-626W/m^2 possible. Herrick put the material through hundreds of melt-freeze cycles with no significant loss of performance. The turning of the cylinder helped the cylindrical crystals to accumulate and shed material evenly; and also this prevented a build-up of crystals on the outer surface of the cylinder through which the heat was exchanged. However, when metal was used for the cylinder material minor cracks on the metal surface proved to be good nucleation points leading to significant crystal growth on the outer surface which needed to be scraped off before each cycle (*ibid.*).

Dehydration of calcium hydroxide has been considered for heat storage by Fujii at al. (1985). Their setup is shown in Figure 2-47 with hydroxide powder packed around finned pipes. They captured heat from combustion gases which surround the cylinders of hydroxide and cause dehydration reaction acting as the charging reaction of the storage. Condensers were used to recover heat of vaporisation from the steam. For discharge, cool water is added to the pipes in the centre of the cylinders and steam is generated while moist air is let into the chamber surrounding the cylinders allowing rehydration reactions. There are fins amongst the material which help only a little with the charging reaction (heat coming from the outside of the cylinder) but are much more helpful with discharging (heat leaving from the centre of the cylinder).

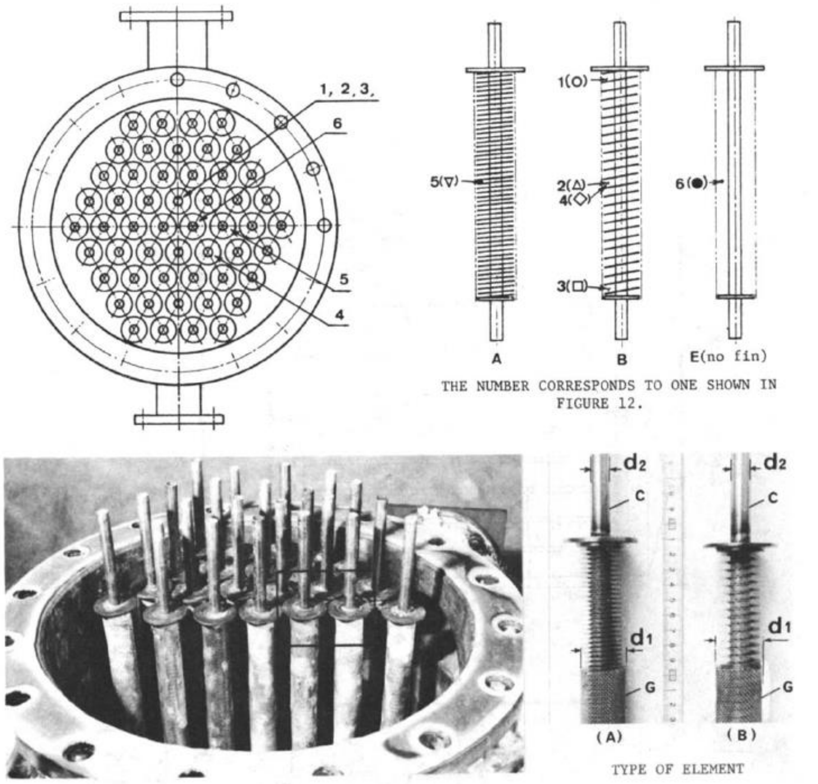

Figure 2-47: Setup for testing calcium hydroxide dehydration.
Source: Fujii et al. (1985).

Examples – stationary and portable

Various attempts to commercialise absorption stores have been undertaken. The Monosorp project at the University of Stuttgart has investigated open bulk honeycomb zeolite to store solar thermal energy (Kerkes and Asenbeck, 2008). The store has to reach 120ºC before the moisture will desorb; if the unit is well insulated then it can act as a sensible heat store over long periods, too.

One company developed an absorption chiller application, shown in Figure 2-48 and explained at ClimateWell.com (2008). This is a batch process where the water is stored and the system is closed. Heat is added to desorb the water from the lithium chloride and the evaporated water is separated off. Crystallisation of lithium chloride means that heat can be stored in the crystals for long periods

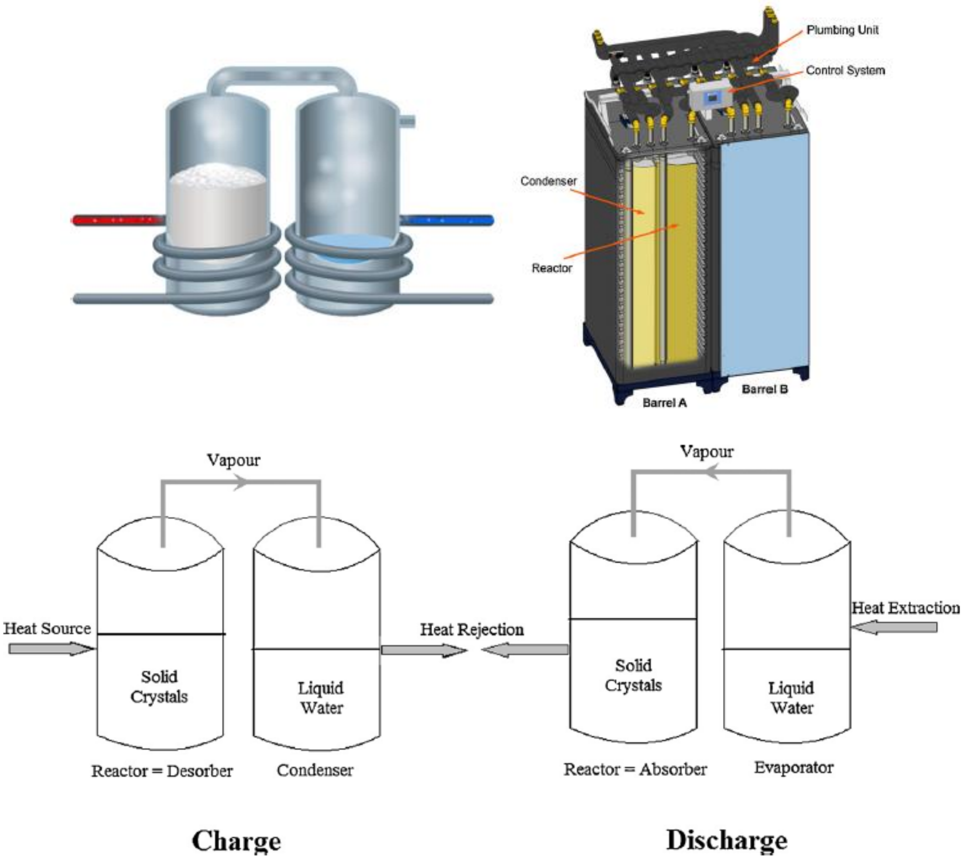

Figure 2-48: Climatewell's absoption chiller thermal store schematic.
Sources: Udomsri et al (2011), Pinel et al. (2011).

Non-Water Sorbents

To maximise surface area, particle suspensions in a slurry have been considered, for example with metal hydrides as described by Chan and Russell (2011). Chan and Russell also describe adsorbent characteristics for silica gel, activated alumina, zeolites, calcium chloride ($CaCl_2$), metal oxides and activated carbon.

Clathrates are an example where the particles intermingle on a molecular scale to store or release heat; research is mainly focussed on tetrabutyl-ammonia-bromide-hydrate (TBAT) working at atmospheric pressure and gas hydrates requiring pressures of up to 50 bar (Hauer et al, 2010). Clathrates are well known to the oil industry as they form pipe-blocking deposits undersea, and also possibly are a large unused energy resource. Typical energy storage values are 250 kJ/kg with melting points near room temperature; they also have a tendency to supercool (Abhat, 1983). They can be used as a phase change slurry for applications including cooling systems (Chatti et al., 2005); research is ongoing to eliminate problems regarding sedimentation of solids (Zhang et al., 2012). Shi and Zhang (2013) find that certain methods for the clathrate crystal production are suitable while others are not due to the binding of crystals to the heat exchanger surface in some cases.

2.7 Latest Research

At an international level, the IEA's Solar Heating and Cooling (SHC) programme covered a task on *Compact Thermal Energy Storage* which ran until December 2015. The summary report from the project notes that while phase change materials are finding niche applications, such as room temperature control and maintaining conditions for medical goods, thermochemical materials remain at initial testing phase (IEA, 2016). The IEA also coordinates international research on topics in district heating and cooling and will soon begin the Annex XII of research running from 2017 to 2020 (IEA DHC CHP, 2016).

In the UK, the Engineering and Physical Sciences Research Council (EPSRC) is sponsoring a number of programmes about energy storage including the Birmingham Centre for Thermal Energy Storage which pursues a broad range of research. The University of Manchester is active in energy storage research particularly on matters of control and network integration (University of Manchester, 2016). The Universities of Sheffield and Southampton are also active in research through the Energy Storage Doctoral Training Centre. Warwick University has been involved in thermal storage research including conductivity enhancement of high temperature stores for solar applications (Warwick University, 2016). Professor Philip Eames of Loughborough University is leading a project entitled "the Future Role of Energy Storage in the UK Energy System". Also, the EPSRC is supporting investigation of pumped heat storage for storage of electricity by researchers at Cambridge University. The Energy Efficient Cities programme at Cambridge University will look at many aspects of energy in city life, including the use of CHP when considering urban design.

2.8 Summary

Heat Sources

The literature review identified that there are significant opportunities for the use of thermal energy storage in order to capture and manage the by-product heat produced from power generation and industry. There is also opportunity to move the operation of heat pumps and chillers away from peak times in order to reduce running costs and reduce the strain on the electrical grid. The location of heat production and demand do not always coincide, and neither do the times of supply and demand. Planning future developments to make use of this heat through transportable heat storage or heat distribution networks could increase energy security and reduce carbon emissions and energy prices.

District Heating Opportunities

Urban areas with district heating networks, or plans to develop them, could take advantage of that infrastructure to link a range of heat sources to sites of heat demand, with storage helping to manage the flow of heat. Heat storage at combined heat and power stations could help the station operators to sell electricity at peak times of pricing rather than following the heat demand. This could also help manage the intermittent electrical output of emerging renewables such as wind turbines and solar arrays.

Policy Environment

The UK government and EU organisations recognise the need to reduce carbon emissions from cities and industry. Making use of waste heat has been recognised a very important part of this in the UK government's updated heat policy. A range of new policies have been introduced, including the Energy Efficiency Directive at EU level as well as UK-specific policies, including the recent introduction of a £320 million capital fund for district heating schemes and an upcoming scheme for industrial heat recovery which will both help to encourage developments in the UK.

High Temperature Store Technologies

Concrete, ceramics and mineral oil have potential as cost-effective high temperature heat storage materials. Molten salts such as metal nitrates have found applications as high temperature phase change materials which could be more widely applied in industry or power stations, low conductivity can sometimes inhibit their application. Chemical reactions may also find applications at these high temperatures provided issues regarding corrosion can be avoided.

Medium Temperature Store Technologies

In general, this temperature band was specified as 60 to 150°C to cover the temperature range of the heat transfer fluid (water) in district heating systems. There are many considerations regarding performance of hot water accumulators as well as the potential for altering the temperature of heat network operation. Alternatives to hot water storage were considered in order to assess heat storage applications. A particular phase change material alternative, erythritol, was highlighted due to its phase change in a temperature band of interest; this is a widely used food additive and therefore has relatively low cost. However, trials of the material were found to have encountered significant problems regarding heat transfer and therefore the possibility of use was discounted.

Low Temperature Store Technologies

Low temperature heat stores such as boreholes and room temperature phase change materials find applications with heat pumps which can raise the temperature of supplied heat to a useful level for applications such as space heating. The thermal capacity of buildings can also be used for heat storage however the response of building occupants can be hard to predict. Paraffin phase change materials are being commercialised in building materials for maintaining room temperatures and helping to move heating demands to off-peak periods.

3 THEORY APPLIED IN CASE STUDIES

Some important principles underpinning the investigation of the case studies are detailed in this chapter. The topics covered range from the thermodynamics of affecting the flows of heat to the economics of implementing heat storage and are grouped as follows:

- Thermodynamics;
- Transmission and storage models;
- Statistical methods;
- Economic analysis;
- Environmental analysis.

3.1 Thermodynamics of heat and storage

3.1.1 Heat capacities and latent heat

With thermal energy storage, the change in stored heat according to temperature rise defines the specific heat capacity. In general, a high specific heat capacity will be beneficial meaning a lower mass of a medium is required to store the same amount of heat.

Phase changes can represent a large change in the thermal energy stored without a change in temperature. If the change of phase can be well managed then a significant absorption or release of heat can be achieved within a narrow temperature change. A high latent heat for a substance will mean a large amount of energy can be stored with only a small amount of the phase change material.

3.1.2 Temperature and quality of heat

The ‘quality’ of heat is an important concept when considering effectiveness of systems with heat transfers. The underlying principle is that thermal energy at lower temperatures is less useful for processes than the same amount of thermal energy at higher temperatures.

For example, thermal power plants produce useful work by tapping some of the energy flow as heat flows from high to low temperature locations. As heat continues to flow, the system and surroundings can move towards a thermal equilibrium meaning less useful work can then be done. In a power plant this energy flow is maintained by adding heat at the hot side by burning fuel and removing heat at the cold side using cooling towers or other heat distribution such as district heating (DH) to carry the relatively low temperature heat away. Maintaining the temperature difference is vital to achieving efficiency of power production.

The heat transfer fluid in power generation systems is often steam and as the steam’s temperature and pressure falls through the expansion process of a steam turbine, the amount of useful work that can be done also falls. The steam is eventually condensed back to liquid and returned to the boiler to gather more heat energy.

3.1.3 Enthalpy

In thermodynamic theory the definition of parameters is key to identifying and understanding process efficiency. One of the most useful functions of state defined is enthalpy, H. Enthalpy is defined for a substance as in Equation 3.9 as the sum of internal energy, U, and the product of pressure, p, and volume, V.

$$H = U + pV \tag{3.9}$$

Differentiating Equation 3.9 and substituting the first law of thermodynamics for the value of dU gives Equation 3.10 where T is the absolute temperature, in Kelvin, and S is the entropy.

$$dH = TdS - pdV + d(pV) \tag{3.10}$$

Enthalpy is a useful relation for studying heat transfers in chemical reactions which often occur under conditions of constant pressure ($dp=0$). Enthalpy is also useful for looking at the behaviour of a substance under conditions where there is no heat exchange ($dS=0$).

In chemistry, the enthalpy change of a reaction determines how much energy is released or absorbed during chemical reactions. The enthalpy change can be found under standard conditions by drawing upon figures for the enthalpies of formation for both the reactants and products under such conditions and finding the difference. The value for enthalpy change is independent of the route of the reaction. Reactions with positive enthalpy changes absorb heat energy and are termed *endothermic*, while reactions with negative enthalpy changes give out heat and are termed *exothermic.* Suitable reversible reactions could be used for thermal energy storage.

3.1.4 Heat engine efficiency and CHP engines

The thermodynamic concept of a heat engine is to capture useful work when heat is transferred from a hot reservoir to a cold reservoir. The operational temperatures of the hot source of heat and the cold sink for heat impact upon the heat engine's efficiency. Reversible engines are conceptualised in thermodynamic theory in order to understand the maximum efficiencies possible.

The ideal power plant performance is given by the operation of a Carnot cycle, where a heat engine operates reversibly receiving all its heat (Q_B) at one temperature, T_B, and giving off all its heat (Q_A) at the temperature, T_A. Its thermal efficiency, η_{th}, is given by Equation 3.11.

$$\eta_{TH} = \frac{W}{Q_B} = \frac{Q_B - Q_A}{Q_B} = \frac{T_B \Delta s - T_A \Delta s}{T_B \Delta s} = \frac{T_B - T_A}{T_B} \tag{3.11}$$

Combined Heat and Power (CHP) systems simultaneously produce useful power and heat. Horlock (1987) constructed a Carnot cycle on a CHP basis, where useful heat is extracted, at an intermediate temperature, alongside the useful work. The three main categories of CHP plant are: reciprocating engines, gas turbines and steam turbines. Deciding on the optimal combination of heat production units is called the 'unit commitment' problem and deciding on how these should run over time is called the 'load dispatch' problem (IEA, 2005b), and clearly the two issues are linked. For example, a smaller reciprocating enginer CHP unit may be favoured to prevent excessive loss of heat and to avoid switching on and off regularly (reducing maintenance costs).

Reciprocating Engines

Figure 3-1 shows how the energy in the natural gas which is burned leaves a reciprocating CHP engine; note that these values are based on the net calorific value of the gas fuel. There are four main heat exchanger (HE) locations to recover the heat from the engine (Clarke Energy, 2014):

i) the first stage air intake intercooler (HE1);
ii) the engine lubrication oil cooling (HE2);
iii) the engine jacket cooling water (HE3); and
iv) the exhaust gas heat exchanger (HE4).

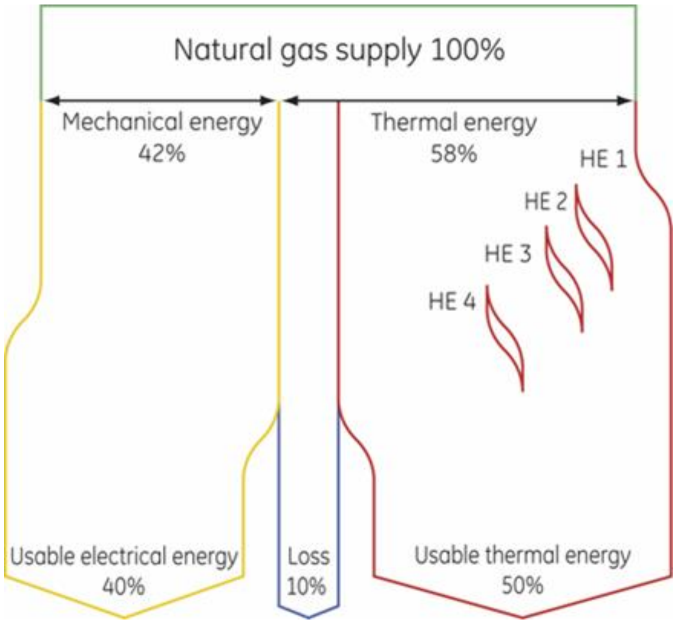

Figure 3-1: Sankey Diagram to show the energy flow through a typical gas-fired CHP engine.
Source: Clarke Energy (2014).

While the first three heat exchangers work well with supplying heat to a heat network at supply temperatures of 90°C and return temperatures of 70°C, the exhaust gases of the engine running through heat exchanger 4 (HE 4) are much higher at around 400 to 500°C (Clarke Energy, 2014). Waste heat boilers in the exhaust can generate high temperature steam. For reciprocating engine CHP units, the proportion of heat and power production remains roughly constant and the engine may be able to turn down to 40% or 50% of its capacity. Reciprocating engines are the technology considered in the case study of Chapter 4.

Steam Turbines

Steam turbines can operate in CHP mode as indicated in the schematic of Figure 3-2. Steam is bled from the turbine to satisfy demand for heat on the heat network and there is a reduction in electricity production when this happens. The fuel burn rate in the boiler is constant for the case study steam turbines featured in Chapters 5 and 6, while in some CHP units the fuel burn rate can be varied. There are limits on the heat output from the CHP due to turbine design and gas-fired boilers are usually used to meet shortfalls in heat production.

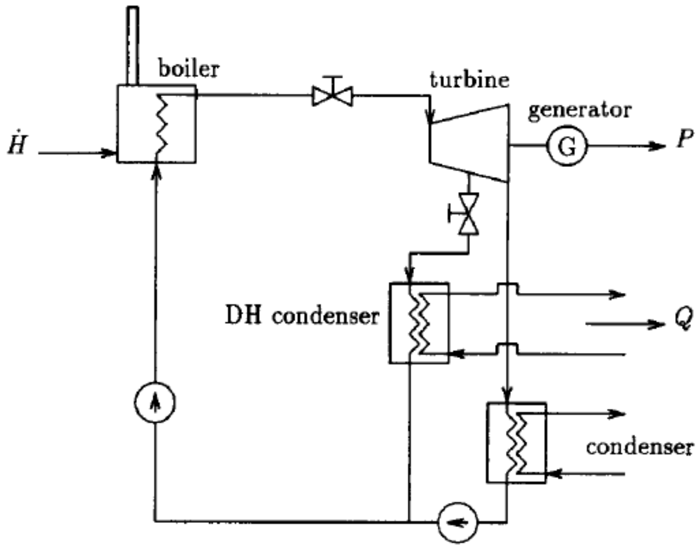

Figure 3-2: An extraction-condensing steam turbine CHP unit for district heating (DH).
Source: Palsson and Ravn (1994).

An increase in the useful heat being drawn, Q_U, from a steam turbine results in an approximately proportional decrease in the electrical work, W. This trade-off is quantified using a factor called the Z-ratio, or Z-factor as in Equation 3.12 (AEA, 2010).

$$W(t) = W_o - \frac{Q_U(t)}{Z} \tag{3.12}$$

Gas Turbines

Although gas turbines have generally lower electrical efficiencies at smaller scales compared to reciprocating engines, there are some advantages such as compact size, lower weight meaning reduced civil engineering costs and fewer moving parts (Pilavachi, 2002). They also produce a higher grade (temperature) of heat and therefore can be better suited to some industrial CHP applications.

Gas turbines can be ‘simple cycle’ without heat recovery from the exhaust or ‘recuperating’ where some of that heat is passed to the combustion air allowing boosted electrical efficiency but less heat available in the exhaust. A schematic of a recuperating gas turbine is shown in Figure 3-3. Lower electrical efficiencies compared to reciprocating engines and the lower-temperature nature of heat demand meant that gas turbine CHPs are not further considered for the case studies in this thesis.

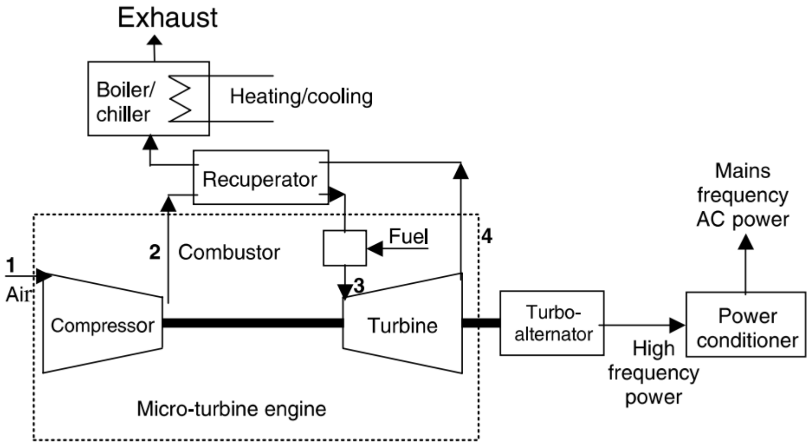

Figure 3-3: Micro recuperating gas turbine schematic.
Source: Pilavachi (2002).

3.1.5 Heat pump efficiency

Electricity, heat, or mechanical work can be used to drive a heat pump moving heat from a heat source (usually ambient air or surface water) to a heat demand. This process is more efficient in terms of heat output than resistive heating since more than one unit of heat can be delivered for each unit of electricity consumed. The ratio of heat delivered to electricity consumed is called the coefficient of performance (CoP), defined as in Equation 3.13.

$$\mathrm{CoP} = \frac{\text{Heat supplied to demand by heat pump}}{\text{Energy input}} \tag{3.13}$$

The ideal performance for a heat pump can be derived by considering a Carnot engine running in reverse. Heat is transferred from a reservoir at temperature T_A through consumption of work, and is passed to a heat sink at the upper temperature, T_U, with a CoP as given in Equation 3.14.

$$\mathrm{CoP} = \frac{T_U}{T_U - T_A} \tag{3.14}$$

In real heat pumps, the CoP is lower than this theoretical maximum and can fall below 1.0 with cold ambient conditions if resistive heating is needed to defrost an air-source heat pump. Note from Equation 3.14 how an increase of temperature difference between the delivery temperature and ambient reduces the coefficient in performance. This has the implication that heat pumps will require more electricity per unit heat delivered in colder months when the demand for delivery of heat is also at its highest. A range of approaches for assessing seasonal performance are given in (HM Government, 2013).

3.1.6 Heat transfer

The three main mechanisms of heat transfer are conduction, convection and radiation. The consideration of these mechanisms will be important in understanding the process of capturing, storing and distributing heat. The heat transfer equation in its simplest form is given by Equation 3.15 where Q is the rate of heat transfer, A is the available area for heat to flow across, ΔT is the temperature difference leading to the heat flow, and U is known as the overall heat transfer coefficient. U can be affected by the temperature difference, ΔT, and other factors (Coulson and Richardson, 1999).

$$Q = U.A.\Delta T \tag{3.15}$$

The heat flow over a small distance, *dx*, can be expresses as in Equation 3.16, where *k* is the thermal conductivity of the medium through which heat is flowing (Coulson and Richardson, 1999).

$$Q = -kA\left(\frac{dT}{dx}\right) \tag{3.16}$$

Equation 3.16 can be applied to a situation with radial conduction in a pipe, which is important for conduction in heat recovery, as well as for the losses from DH pipes. Hence the heat flow at radius *r* is given by Equation 3.17, where *l* is the pipe length.

$$Q = -k.2\pi r.l\left(\frac{dT}{dr}\right) \tag{3.17}$$

It is appropriate to model the water in the DH pipe as a well-mixed fluid (uniform temperature) with well-insulated pipe walls having a low conductivity, *k*. This equation will also apply for heat losses from hot water cylinders. The analysis could also be extended to a spherical geometry for heat transfer into spherical particles which could be used as a heat storage medium.

3.1.7 Conduction and convection

Convection is the movement of fluid on a macroscopic scale carrying excess heat. *Natural convection* is caused by buoyancy forces due to thermal expansion with excess heat and *forced convection* has a different cause such as an agitator (Coulson and Richardson, 1999). Usually, near a surface the currents die down due to roughness of the surface and conduction of heat is the main mechanism through a film at the surface (*ibid.*).

The balance of conduction and convection will be particularly important for assessing the heat loss from hot water accumulators; the natural convection of fluid inside the accumulator is one part of the heat loss assessment and forced convection of air on the outside of the tank due to wind could be another factor.

3.1.8 Boundary layers

Flow of the heat transfer fluid (HTF) across a heat transfer surface is affected by boundary layer effects where the fluid adheres due to friction. Figure 3-4 demonstrates this effect by the consideration of a fluid moving past a plate with a sharp edge. In addition to affecting heat exchange surfaces, the boundary layers on DH pipe circumference will add hydraulic resistance and reduce flow (raising the necessary pressure for pumping).

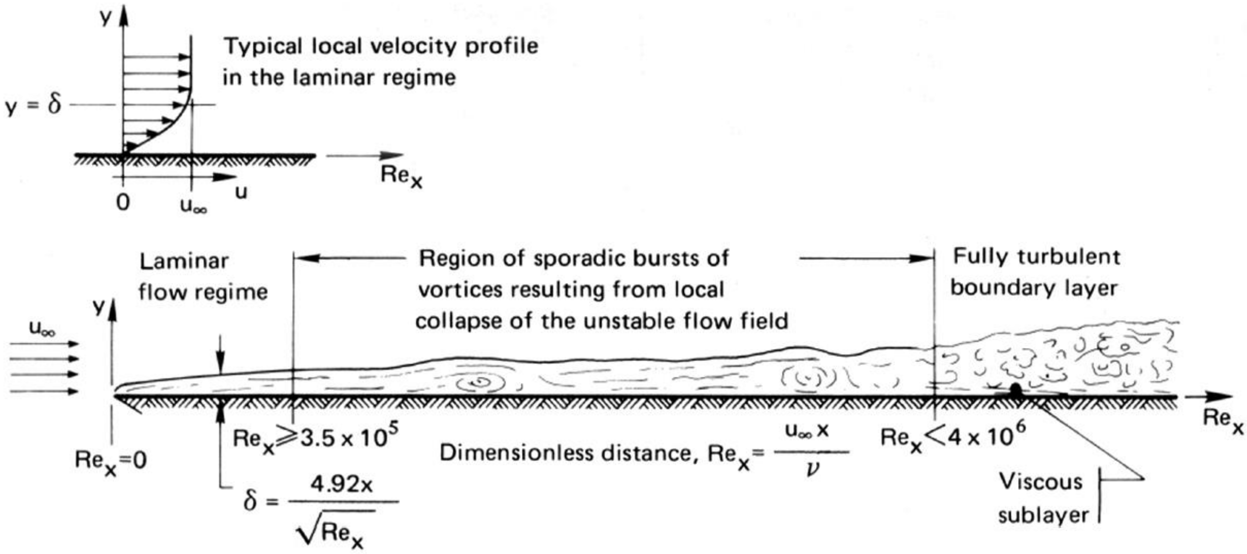

Figure 3-4: Boundary layer effect.
Source: Lienhard and Lienhard (2011).

3.1.9 Heat Exchangers

It is necessary in some circumstances to pass heat from one fluid to another, such as when the heat transfer fluid has to be turned back towards its source in a closed loop. The effective transfer of heat usually requires a large surface area and a short distance for the heat to cross (thin boundary walls).

One simple distinction of heat exchanger types is the use of parallel flow and counterflow heat exchangers, which results in different rates of heat transfer, as seen in Figure 3-5.

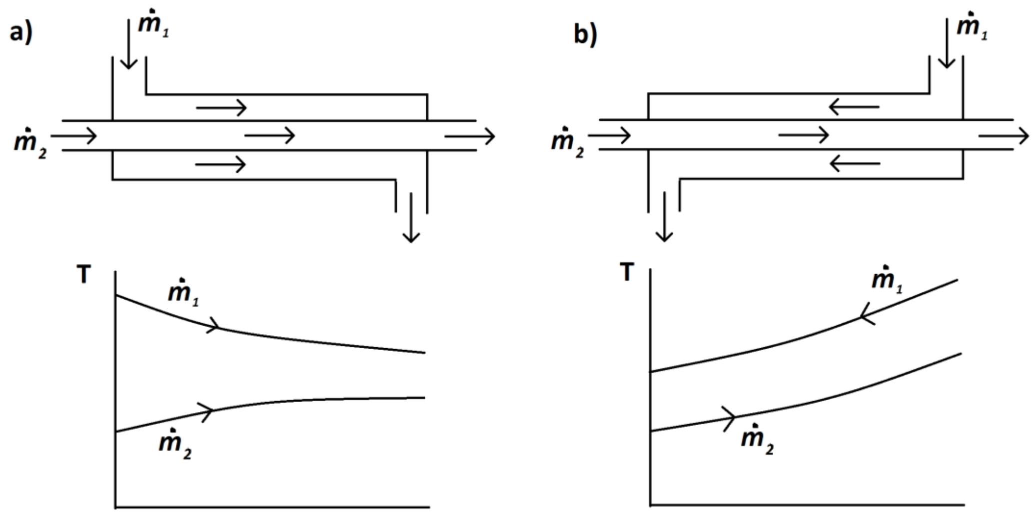

Figure 3-5: Flow arrangement and characteristic temperature changes in (a) parallel and (b) counter flow arrangements of concentric circular tubes.
Source: adapted from University of Sheffield issued lecture notes.

The most common heat exchanger type is the shell-and-tube type where usually many tubes carry one fluid through a volume containing another fluid with which heat transfer occurs.

The use of "heat pipes" can result in much higher thermal conductivities (Ammar et al., 2012) with an evaporative and condensing cycle taking place. A review of modern heat pipe technology is given by Vasiliev (2005). The principle is that there is liquid evaporation at the heat source, there is vapour condensation at the heat sink and the liquid is transferred back along the porous wick around the circumference of the pip by means of capillary action (*ibid*.). Figure 3-6 illustrates this principle.

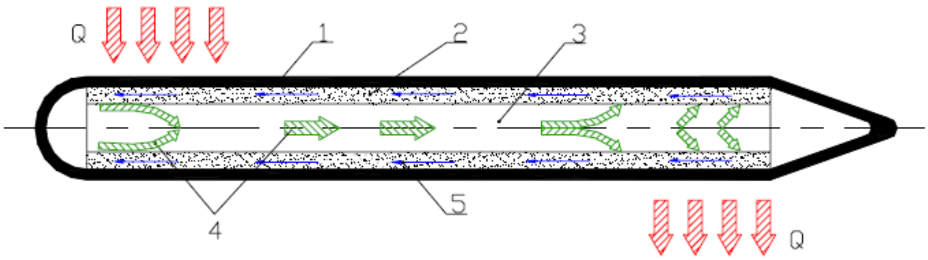

Figure 3-6: A schematic of a conventional heat pipe.
Source: Vasiliev (2005). (1) = heat pipe case, (2) = porous wick, (3) = vapour channel, (4) = vapour, (5) = liquid.

The low resistance to the vapour allows for easy heat transfer in that phase. Heat pipe heat exchangers can be smaller due to better heat transfer rates; they can also be run backwards to provide a cooling function.

3.1.10 Heat pump heat exchangers

At the 14th International Symposium on District Heating and Cooling in Stockholm in September 2014 some interesting concepts for heat pump heat exchangers and super-large DH schemes were presented. The absorption heat exchanger concept and its applications was further detailed by Fang et al. (2015) as shown in Figure 3-7. An alternative is to use an electrical heat pump to upgrade heat from a low temperature heat network in order to achieve lower return temperatures.

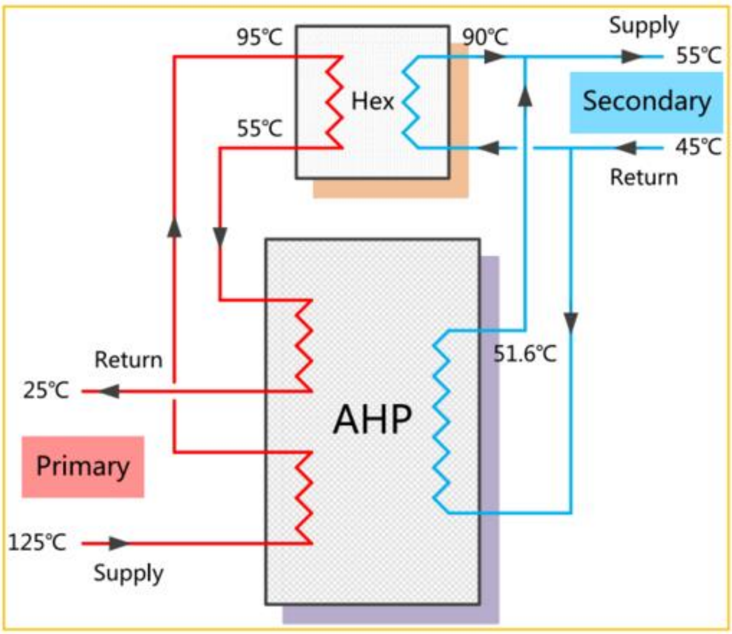

Figure 3-7: Concept for an absorption heat exchanger.
Source: Fang et al. (2015).

The heat pump heat exchanger concept was introduced with the potential to achieve very large difference between supply and return temperatures on the primary side of the heat distribution system. This may have applications for effectively using waste heat in heat networks.

3.2 Physical Transmission and Storage Models

3.2.1 Heat networks

Traditional DH networks operate using steam or hot water at high temperatures which can exceed 100°C, whereas there are also lower temperature systems now which allow for a greater choice in heat sources as well as for the reduction of heat losses. Table 3-1 shows typical design data for the primary and secondary distribution systems where the secondary distribution system circulates heat within the buildings for a bulk heat exchanger to the point of use.

Table 3-1: DH Primary and Secondary System Rating and Design Data.
Source: Swedish District Heating Association (2004).

District Heating System	Rating Data	Design Data
High-temperature system	100°C, 16 bar, Differential pressure 6 - 1.5 bar	120°C, 16 bar
Low-temperature system	80°C, 6 bar, Differential pressure 2 – 0.5 bar	80°C, 6 bar
Secondary-temperature system	< 60°C, 6 bar, Differential pressure 2 – 0.5 bar	80°C, 6 bar

Pipeline diameters affect the heat transport capacity, the heat losses due to convection and the conduction losses. The flow speeds in the pipes are kept low, of the order 1-3m/s, and while faster speeds would allow greater heat loads, the risk of hydraulic shocks damaging the pipes is significant. Table 3-2 describes typical properties of DH pipes including cost estimates associated with laying them.

Table 3-2: The approximate properties of DH pre-insulated pipes.
Source: Ramboll (2013).

DN mm	Flow (m/s)	Capacity (MW)	Price per km trench (£M/km)	Price per km per capacity (£/km/MW)	Price per km per annual sale (£/km/MWh/a)	Heat loss per km (%/km)
100	1.0	2	0.5	228567	57	2.96
200	1.5	13	0.9	65125	16	1.08
300	2.0	38	1.4	37400	9	0.5
400	2.3	69	1.8	25970	6	0.28
500	2.6	125	2.3	18595	5	0.15
Pre-insulated pipes			Supply temperature		120 ºC	
max design app 130 ºC			Return temperature		60 ºC	
Variable flow pumps			Transmitting base load			

In heat networks with indirect connections there is complete hydraulic separation of the heat transfer fluid that is distributed to buildings (the primary side) from the fluid that circulates inside the buildings to heating and hot water systems (the secondary side). The supply temperature on the primary side can also be lowered in the instance of higher ambient temperatures, as shown in Figure 3-8. The variation of differential pressures with distance along the pipe is shown in Figure 3-9; the consumers at the periphery of the heat network have the lowest pressure differential at their substations.

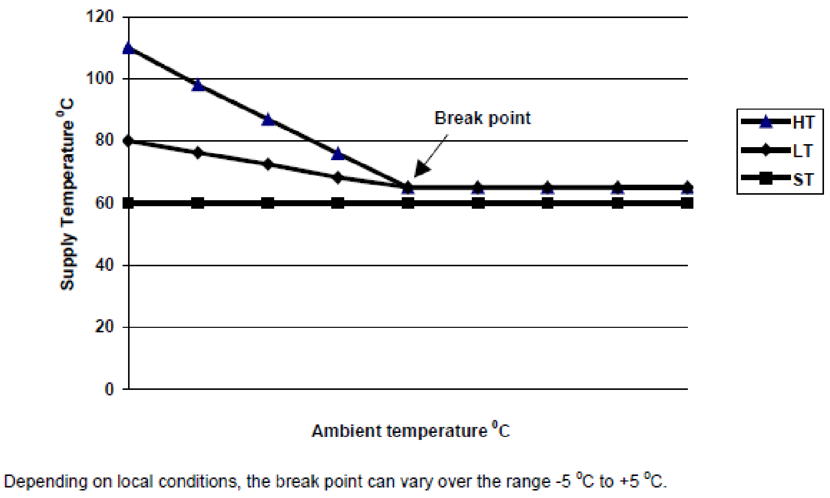

Figure 3-8: How supply temperatures tend to be changed according to ambient temperatures. Source: Swedish District Heating Association (2004).

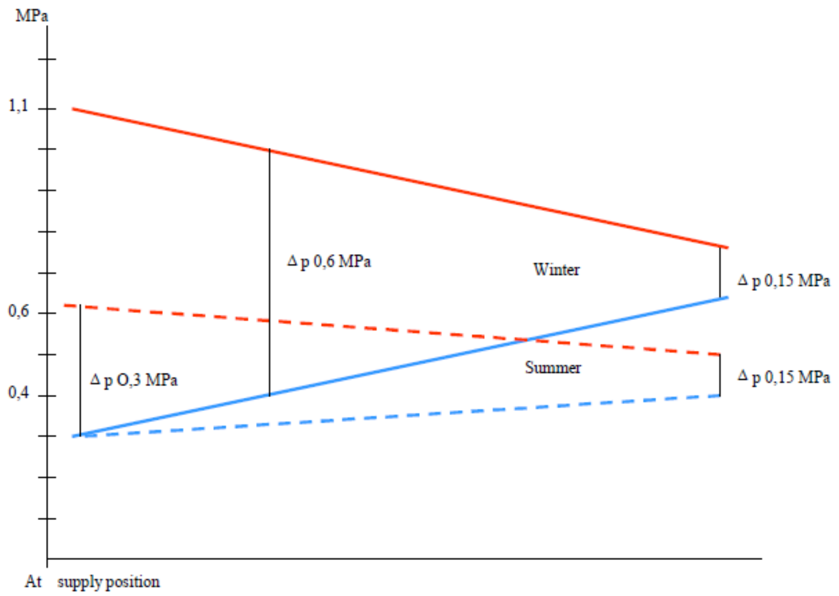

Figure 3-9: The variation of differential pressure between supply and return pipes according to distance from supplier. Source: Swedish District Heating Association (2004).

For operational management the flow, temperature and pressure of the DH water is monitored; these parameters are affected by the demand from the consumers. Changes in the fluid flow through the heat exchangers at the customer feed back hydraulically to the whole system by altering the pressure. These pressure waves move around a thousand times faster than the water in the system itself moves and hence changes to supply and return water temperatures caused by demand effects take much longer to affect the whole system.

On a DH system, operation to load the system with heat (by raising the temperature) needs to account for how long that hot water will take to travel to the point of demand which it serves. Also varying amounts of this hot water will be tapped along the way for the other heat sources that are connected.

Larsen et al. (2002) identify three steps for each computing iteration for DH network simulation. Heat networks can have complex structures which change over the years. Running simulations of pressure, temperature and mass flow on these networks requires a lot of computational power. Methods have been developed to aggregate the networks into simpler forms whilst attempting to avoid loss of accuracy of results, for example see Larsen et al. (2002).

The cost of maintenance becomes an increasing burden as a heat network ages. Research by Gilski et al. (2014) describe how a high failure rate in Warsaw DH network was reduced over time, as shown in Figure 3-10, through a range of measures including thicker pipe walls from 1986, reverse osmosis and demineralisation from 1995 to reduce water corrosiveness. Gilski et al. also describe how a new initiative is working to help predict and prevent failure through documentation of previous failures and categorisation of the risk of failure for different sections to prioritise replacement programmes.

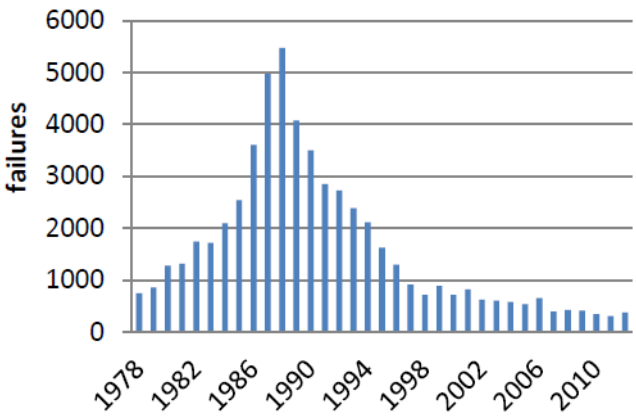

Figure 3-10: Annual failure rate in Warsaw DH network from 1978 - 2012.
Source: Gilski et al. (2014).

3.2.2 Heat demand diversity

When planning a DH network it is important to minimise the pipe diameters to achieve the best economic return. The necessary diameter is defined by the peak heat load that must be supplied through the pipe. When multiple buildings are downstream of a pipe section, the peak expected demands of those buildings are added together and a ‘diversity factor’ applied to acknowledge that the pipe capacity can be reduced as it may be very unlikely for the peak demands of all those buildings to coincide. Application of a diversity factor also helps avoid oversizing of heat production plant and therefore reduces cost at the DH energy centres.

In this thesis it is important to consider the diversity factor when scaling up the heat demand from one site to a number of sites as the diversity of a connected network will reduce the scale of peaks in heat demand relative to the total demand and this will affect the advantages of using heat storage. Danish standard DS 439 is widely used for diversity calculations following Equation 3.18 which applies to a number of dwellings, N, and suggests that the overall peak demand per dwelling falls quickly as the number of properties increases (CIBSE and ADE, 2015).

$$P_{\max}(\text{kW}) = 1.19 \times N + 18.8 \times N^{0.5} + 17.6 \qquad (3.18)$$

Where P_{max} is the total heat required in kW and N is the number of 'normal dwellings' as defined by some simple criteria.

In the situation of non-domestic buildings and large multi-residence complexes there may be energy data available at a building level and a large amount of diversity will be already represented in these.

3.2.3 Store and heat loss models

Raising the temperature of the medium raises the amount of sensible heat energy stored, as in Equation 3.19, where *m* is the mass of medium, *c* is the specific heat capacity, and ΔT is the change in temperature. Most often in heat networks the medium of heat transmission or storage is liquid water. Hot water from the supply side of the network resides at the top of the tank while cooler water from the return side of the network resides at the bottom due to density differences. Variation of the specific heat capacity and density of water with temperature can be found in CIBSE Guide C (CIBSE, 2007). For phase changes in a material, the latent heat is given by Equation 3.20 where *m* is the mass of the material, and *l* is its specific latent heat of phase change.

$$\Delta E = m.c.\Delta T \tag{3.19}$$

$$\Delta E = m.l \tag{3.20}$$

For hot water stores in the case of Sheffield's low carbon heat network, it is appropriate to assume a temperature difference between supply and return temperatures of DH water to the store of ΔT=40 K. A 90% availability of the store is assumed since around 10% of the water resides in a mixed temperature zone (IEA, 2005b) that has to be ignored as it cannot be discharged on the supply or return sides of the network. A necessary volume of water, *V*, to store 1 MWh is then given by Equations 3.19 to 3.23 using the specific heat capacity and density of water at 90°C from CIBSE (2007).

$$\Delta E = m.c.\Delta T \tag{3.19}$$

$$1\ \text{MWh} = 1{\times}3600\ \text{MJ} = 0.9 \times m \times (4.2080\ \text{MJ/tonne.K}) \times 40\text{K} \tag{3.21}$$

$$m = 23.76\ \text{tonnes} \tag{3.22}$$

$$V = \frac{m}{\rho} = \frac{23\,760\ \text{kg}}{965.3\ \text{kg/m}^3} = 24.6\ \text{m}^3 \tag{3.23}$$

Water stores and stratification

Three factors affect the temperature gradient in the thermocline (mixed temperature) zone for hot water stores (IEA, 2005b):

- mixing at the inlet;
- natural convection; and
- heat diffusion and conduction.

The location of the inlet and the inlet velocity has important effects; this will cause differences in the degree of mixing for the hot and cold water. The Richardson number is a dimensionless ratio that compares the potential and kinetic energy differences in a fluid mixture and can be written as Equation

3.24 where g is the acceleration due to gravity (m.s^{-2}), *ß* is the thermal expansion coefficient (K^{-1}), ΔT is the temperature difference (K), L is a characteristic length (m), and v is a characteristic fluid velocity (m.s^{-1}) (IEA, 2005b).

$$\mathrm{Ri} = \frac{g.\beta.\Delta T.L}{v^2} \tag{3.24}$$

A Richardson number value of at least 0.25 is expected as necessary to avoid excessive mixing, limiting an inlet velocity to around 1.2 metres per second or less (IEA, 2005b). Stratification can also occur in solid media, such as gravel beds, but since there is no flow there is no buoyancy-induced mixing and different temperatures can occur in different parts.

Heat conduction

Initially, a model was created for the interface of hot and cold water with a step function in temperatures: 70°C at the bottom of the tank and 110°C at the top. This one-dimensional tank model does not consider the losses at the walls of a vertical axis cylinder tank. The heat conduction can be modelled using the heat flow Equation 3.16. In the model heat flow raises and lowers temperature of affected fluid elements, as in Equation 3.25.

$$Q\Delta t = m.c_p.\Delta T \tag{3.25}$$

This model, calculated using elements in Microsoft Excel, leads to a broadening of the thermocline in the tank over time, as illustrated in Figure 3-11. The central part of the thermocline is likely to be too cool to act as supply water and too warm to act as return water and therefore becomes a region of unusable heat. The edges of the thermocline may be adequate for supply between say 105 and 110°C and return between 70 and 75°C. In this way, the edges of the thermocline may disappear from the tank.

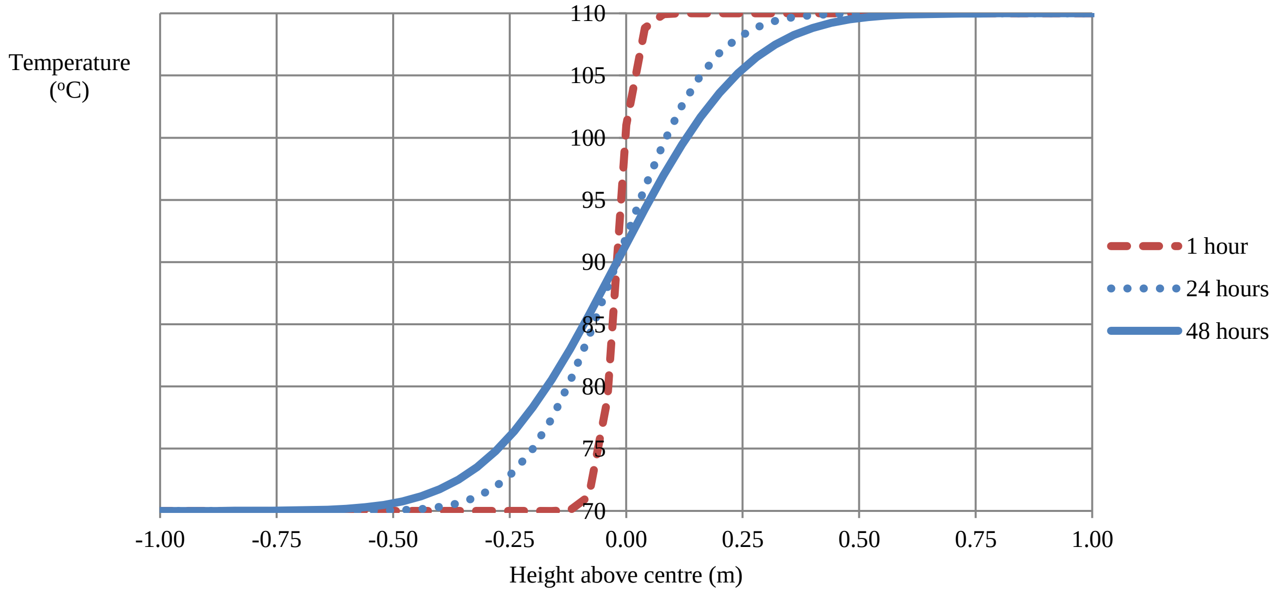

Figure 3-11: Modelled development of thermocline.

This initial model is simple and informs the rate of heat loss to be expected in the simulations of the case study chapters. The step change temperature heat diffusion problem can also be solved analytically, and the solution presented for a diffusion problem by Zielinski (2006) is adapted and reproduced in Equations 3.26 and 3.27 for the heat conduction problem where at t=0, the temperature for negative x values is T_1 and it is T_2 for positive x values.

$$\rho A c \frac{\partial T}{\partial t} = kA \frac{\partial^2 T}{\partial x^2} \tag{3.26}$$

$$T(x,t) = \frac{(T_2 + T_1)}{2} - (T_2 - T_1).\left(\frac{1}{\sqrt{\pi}} \int_0^{\frac{x}{\sqrt{\frac{4kt}{\rho c}}}} e^{-y^2} \right) \tag{3.27}$$

The solution of Equation 3.27 leads to a characteristic width for the thermocline given in Equation 3.28, for which values over time were calculated as given in Table 3-3.

$$x = \sqrt{\frac{4kt}{\rho c}} \tag{3.28}$$

Table 3-3: The development of characteristic thermocline width over time.
Values calculated assuming k = 0.58 W/m.K, ρ = 965kg/m^3, and c = 4208 kJ/kg.K.

Time (hours)	Characteristic width (m)
1	0.045
24	0.222
48	0.314

So in this conduction-only model the thermocline is predicted to broaden at a rate proportional to time to the power 0.5; the spreadsheet model agrees with this analysis.

Losses from the tank’s surface are important too and cause movement around the tank due to loss of temperature and increasing density at the tank walls. Turbulence during filling and linked to the movement of the thermocline relative to the walls adds to the effective conductivity (Verda and Colella, 2011).

Losses at the tank surface

A 1D radial conduction model was also built in Microsoft Excel to model heat losses at the tank surface. The analysis is based on a tall cylinder store which is a typical design due to benefits of minimising the footprint of the store as well as the surface area of interface between the hot water at the top of the tank and cold water at the bottom. Heat loss through the steel shell of the tank to the surroundings is investigated here.

The model, like the one for the thermocline, allows heat to move between elements of the fluid as well as in this case into the steel wall of the cylinder and the insulation that is on the outside of the tank.

Figure 3-12 shows the case where the steel lining and insulation surrounding the tank is initially at 70°C representing a state at which the tank wall has reached the same temperature as the minimum temperature possible for the internal fluid (70°C). The radius of the cylinder is 3.5m and this parameter defines the surface area through which the heat can escape.

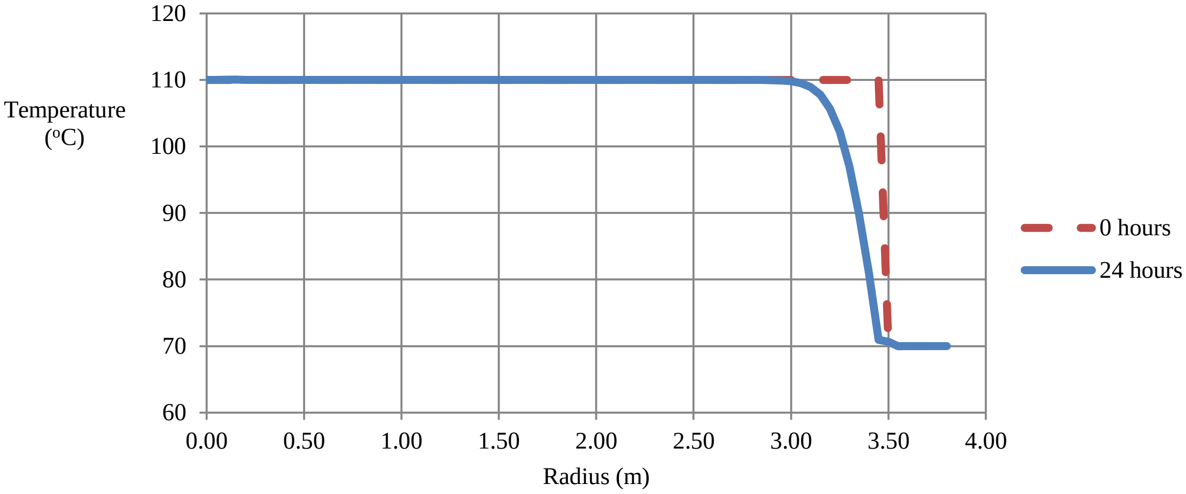

Figure 3-12: Heat losses at the edge of the tank.

The temperature loss shown after 24 hours in Figure 3-12 affects the buoyancy of the water by increasing the density. The cooler water at the edge of the tank relative to the middle will have greater density and sink within the tank leading to some circulation, but this modelling does not account for this.

There are exact equations for steady state conduction through a cylinder wall, and these can be derived using the heat flow equation expressed as in Equation 3.29 where $A_r = 2\pi rL$ with reference to the geometry shown in Figure 3-13.

$$\dot{Q} = -kA_r\frac{dT}{dr} \tag{3.29}$$

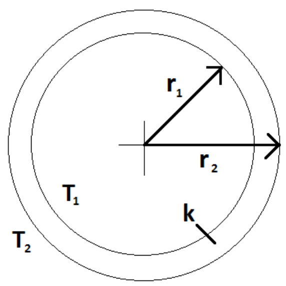

Figure 3-13: Pipe dimension definitions for conduction through a pipe or cylinder wall.

Rearranging the formula and integrating between T_1 at $r = r_1$ and T_2 at $r = r_2$ gives Equations 3.30 to 3.32.

$$\int_{r_1}^{r_2} -\frac{\dot{Q}}{2\pi Lk}.\frac{1}{r}dr = \int_{T_1}^{T_2} dT, \tag{3.30}$$

$$-\frac{\dot{Q}}{2\pi Lk}[\ln r_1 - \ln r_2] = [T_2 - T_1] \quad (3.31)$$

$$\dot{Q} = 2\pi Lk \, \frac{(T_1 - T_2)}{\ln({}^{r_2}/_{r_1})} \quad (3.32)$$

The rate of heat transfer through layers with thermal resistance, R_{th}, can be represented in a similar way to electrical current passage through a resistance as in Equation 3.33.

$$\dot{Q} = \frac{\Delta T}{R_{th}} \quad (3.33)$$

For a flat slab the thermal resistance is R_{th}=L/kA and for a pipe the thermal resistance as given in Equation 3.34 and for multiple layers the heat flow becomes that given in Equation 3.35.

$$R_{th} = \frac{\ln(r_2/r_1)}{2\pi.L.k} \quad (3.34)$$

$$\dot{Q} = \frac{\Delta T_{overall}}{\sum R_{th}} \quad (3.35)$$

These are steady state flow equations and therefore need to be treated appropriately and calculation of models element by element can be useful for situations that cannot be solved through use of equations.

3.3 Statistical Methods

3.3.1 Statistical Treatment of Demand Data

Testing Correlations

The pattern of a series of points (x_i,y_i) can be tested for interdependence between the x_i and y_i by calculating the *sample covariance*, V_{xy}, given in Equations 3.36 to 3.38 (Riley et al., 2002). While writing this out explicitly for the N points gives Equation 3.39 (*ibid.*).

$$V_{xy} = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y}) \quad (3.36)$$

$$= \overline{(x_i - \bar{x})(y_i - \bar{y})} \quad (3.37)$$

$$= \overline{xy} - \bar{x}\bar{y} \quad (3.38)$$

$$V_{xy} = \frac{1}{N}\left(\sum_{i=1}^{N} x_i y_i\right) - \frac{1}{N^2}\left(\sum_{i=1}^{N} x_i\right)\left(\sum_{i=1}^{N} y_i\right) \quad (3.39)$$

To get a more meaningful test, that is independent of the units, this quantity is divided by the standard deviations of each variable, given by Equation 3.40, to produce the *sample correlation*, r_{xy}, as described in Equation 3.41 (*ibid.*)

$$s_x{}^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2 \quad (3.40)$$

$$r_{xy} = \frac{V_{xy}}{s_x s_y} \quad (3.41)$$

The sample correlation, r_{xy}, can vary between +1 and -1; the extremes of this range represent perfect positive and negative correlations respectively while a value of zero represents no correlation whatsoever.

3.3.2 Using Degree Days

Degree days are defined with respect to a base temperature at which a building heating system is no longer required due to sufficient internal sources of heat. For the UK, the base outdoor temperature is usually defined at 15.5°C (Carbon Trust, 2012), whereas the temperatures inside buildings will be few degrees higher due to internal heat gains.

The degree days figure is calculated as a cumulative product of the temperature difference between the outdoor and base reference temperature while the outdoor temperature is less than the base temperature and the duration of this difference. This integral is illustrated as the blue area in Figure 3-14.

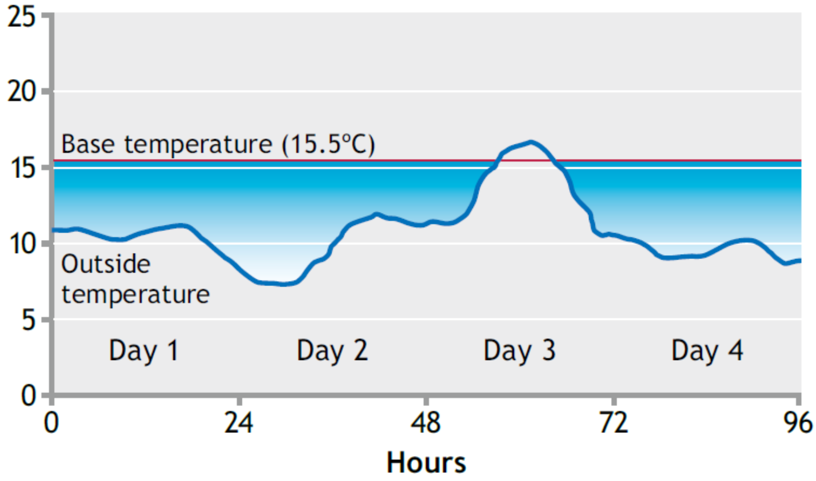

Figure 3-14: Illustration for calculation of degree days.
Source: Carbon Trust (2012).

3.4 Economic Analysis

3.4.1 Fuel costs

The use of heat storage can reduce the need for primary fuel consumption and the economic benefit can be assessed using the energy bills of the relevant stakeholder. Commercial sensitivity sometimes means that these fuel costs need to be estimated. The cost of gas and electricity will have the greatest influence on the case studies in this project. Additional energy taxes will be explored in Sections 3.4.3 and 3.4.5. The Department for Business, Energy and Industrial Strategy (BEIS) provides regular statistics on energy prices and also projections of future energy prices and these are referred to in economic analyses in the case studies.

3.4.2 Electricity revenues

The UK's private electricity trading agreements mean electricity sale price is difficult to estimate (Fragaki et al., 2008), although an indication of prices can be gained from the spot market prices which are openly published and constitute around 3 % of electricity trading (Wilson et al., 2011). Small CHP plants (below 50 MW_e capacity) access the electricity market through 'consolidators' acting on their behalf in the power exchange market and this is estimated to diminish revenues by around a quarter compared to those achieved by large power stations (Toke and Fragaki, 2008). The small size of distributed CHP generators means that they effectively appear as 'negative demand' on the electricity system and they are not subject to the Balancing and Settlement Code in the UK which would give them penalties if they went off-line at short notice (Toke and Fragaki, 2008). It can be much more profitable for these small generators to directly supply electricity to local businesses, achieving higher prices for the generator and lower prices for the consumer, provided the connecting high voltage infrastructure works are affordable.

Triad periods in the winter months are also used for payments in some power contracts. Each year, following the period from November to February inclusive, the National Grid publishes details of when the triad periods occurred representing the half-hour with the highest demand, the half hour with the next highest demand that didn't fall within ten days of the first, and the third highest that didn't fall within ten days of either of the highest two (National Grid, 2015). Large, non-domestic electricity consumers usually have electricity bills that include higher charges for day consumption compared to night time consumption and include red, amber and green tariffs according to time of week which are set by the distribution network operator (DNO) for a region representing the Distribution Use of System (DUoS) costs. Large non-domestic electricity consumers may also pay triad (Transmission Network Use of System, TNUoS) charges depending on the amount of electricity consumed in those periods and for this reason these provide incentives for on-site electricity production or demand reduction measures for large electricity consumers such as a university.

3.4.3 Heat revenues

For selling heat there are various ways of agreeing upon a price. For example with an extraction-condensing steam turbine plant, where the use of heat results in a roughly proportional reduction in power production then the heat user could pay the equivalent of lost electricity income. The allocation of profits between electricity production and heat production will depend on the market conditions for each; if the profitability of a CHP falls mainly onto the heat side then that will encourage development of heat networks the most, as was the practice in Denmark (Frederiksen and Werner, 2013).

Customers joining a heat network in the UK are likely to expect a cost saving compared to using gas boilers as a consequence of using what is widely perceived as a novel technology. In UK DH schemes, there is a wide variation of contract structures and prices for household customers found by Which (2015), who went on to calculate the equivalent overall heating costs for a dwelling as given in Table 3-4. Large commercial customers are likely to require lower heat costs due to low gas cost counterfactuals. The cost per MWh for many Swedish DH systems are given in Figure 3-15, of which Lulea (where the lowest costs are) has a large input of industrial waste heat (Frederiksen and Werner, 2013).

Table 3-4: Estimated heat costs calculated for a two-bed flat including boiler maintenance and replacement. Source: Which (2015).

Heat Source	Price for delivered heat (p/kWh)
DH	5.51-14.94
Gas heating	9.55-11.60
Electric heating	21.91-22.99

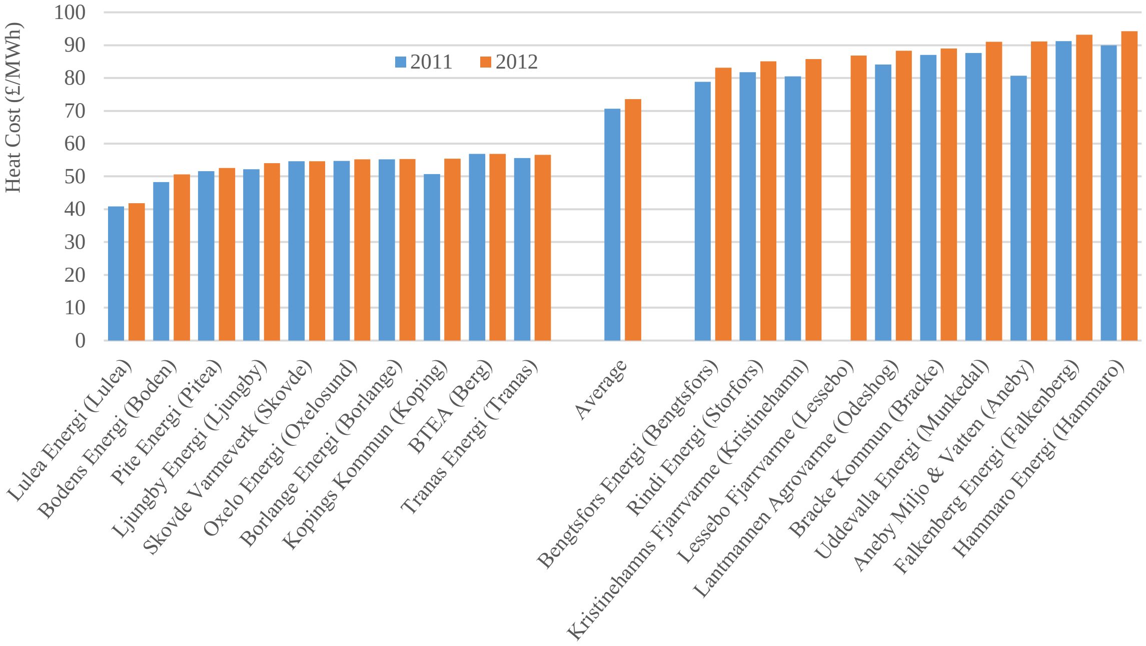

Figure 3-15: Histogram of DH prices offered by Swedish utility companies as of 2011 and 2012. Source: Frederiksen and Werner (2013). September 2016 exchange rate of 10.75 SEK/GBP (Travelex, 2016).

3.4.4 Supporting incentives for CHP and renewable heat

CHP plants can receive incentives through Climate Change Levy exemption, Enhanced Capital Allowances and Business Rate exemption schemes (DECC, 2015f). Renewable CHP plants may also qualify for Renewable Obligation Certificates, the Renewable Heat Incentive and the Feed-in Tariff schemes (DECC, 2015f). Hydrocarbon Oil Duty Relief is also available to oil-fired CHP units (DECC, 2015f). A recent review of policy options found that a bespoke natural gas CHP support policy was not required (DECC, 2014j). Energy-from-waste plants also receive revenue for the disposal of waste, known as ‘gate fees’ (WRAP, 2014). The various tax and incentive schemes are further detailed below.

Climate Change Levy (CCL)

CHP schemes achieving partial or full certification as “good quality CHP” under the CHPQA programme qualify for exemption from the main rates of CCL on the fuel they use and the direct and self-supplies of power output generated (with a scaling back if Quality Index or electrical efficiency thresholds are not met) (DECC, 2015f). The boundary of the CHP scheme can be drawn around auxiliary boilers used for DH as described in CHPQA Guidance Note 11 (CHPQA, 2014a) and provided that the overall efficiency criteria are met, the fuel used is exempt from CCL. Renewable electricity supplied to the grid used to be eligible for Levy Exemption Certificates, but this eligibility was removed from 1st August 2015 (Ofgem, 2015c). Loss of CCL exemption certificates for electricity sold to grid cost gas CHP units approximately 0.45p/kWh sold (DECC, 2013s).

Enhanced Capital Allowances (ECAs) and Business Rate Exemption

ECAs allow investments to be written off against taxable profits providing economic incentives for investment in equipment such as good quality CHP (DECC, 2015f). Waste heat recovery systems will become eligible after an announcement in the UK government Budget 2015 (gov.uk, 2015b). ECAs are not available to businesses whose main turnover is from selling electricity to unknown consumers (DECC, 2015f), therefore the only eligible CHP units considered in this study would be those at the University of Sheffield. Business rating exemption applies for specific plant and machinery associated with good quality CHP units (DECC, 2015f).

Renewable Obligation Certificates (ROCs) and Renewable Heat Incentive (RHI)

Ofgem issues ROC incentives to renewable electricity generators in response to UK policy to achieve renewable energy targets. For CHP generators, the overall efficiency (generally boosted by drawing more heat) influences the number of ROCs received. Electricity suppliers which do not present their required quota of ROCs have to pay a penalty called the 'buy out price' for each missing ROC (Gov.uk, 2013), equal to £44.33/ROC for the year 2015/16 (Ofgem, 2015). The number of ROCs awarded to a renewable CHP generator relates to Equation 3.42 (CHPQA, 2013b), with coefficients X and Y depending on CHP plant age, output capacity and technology type, giving a "Quality Index" (QI) linked to the overall efficiency of the plant.

$$\text{Quality Index, QI} = \text{X} \times \eta_{\text{power}} + \text{Y} \times \eta_{\text{heat}} \qquad (3.42)$$

where η is the efficiency of heat or power production on a gross calorific value basis.

The factors X and Y are updated periodically in order to maintain high standards of CHP efficiency, for example ensuring that the QI cannot exceed 100 without meeting the primary energy saving thresholds (>0% for schemes less than 1MWe or 10% for >1MWe schemes) and the minimum overall efficiency of 35% on the gross calorifica value basis (CHPQA, 2016).The 2016 review of these factors included a significant reduction in the X coefficient applicable to new schemes similar to the biomass CHP of chapter 5 (*ibid.*).

Each renewable CHP power station only receives the maximum number of ROCs if it achieves a QI of 100 or above, otherwise the Qualifying Power Output (QPO) is a reduced fraction of the total power output according to the value achieved. There is an exemption for new CHP units connected to DH where the target QI is 95 over the first 5 years (CHPQA, 2013b) allowing time for heat loads to be added. The QPO receives a number of ROCs depending on the commissioning year as given in Table 3-5. There are no ROC certificates for Energy from Waste electricity-only plants (Gov.uk, 2013b). Existing generating stations that pre-date the Renewable Obligation, such as Bernard Road Energy Recovery Facility in Sheffield, will not receive support from ROC incentives after 31st March 2027 but newly commissioned plants receive 20 years of support (Gov.uk, 2015d).

Table 3-5: The ROC banding levels 2013-2017 for selected technologies.
Source: Gov.uk (2013b) and Ofgem (2015b).

	Support level for QPO (ROCs/MWh$_e$)			
Band	2013/14	2014/15	2015/16	2016/17
Dedicated biomass	1.5	1.5	1.5	1.4
Dedicated biomass with CHP	2	2	1.9	1.8
Energy from waste with CHP	1	1	1	1

The qualification of CHP for incentives often relies upon meeting quality assurance standards, for example heat metering of the output stream must meet standards as set out in CHPQA Guidance Note 16 (CHPQA, 2013e).

The RHI supports heat from renewable sources such as biomass boilers and heat pumps. The RHI scheme financial incentives for the production of heat from renewable fuels including biomass. In March 2016, the UK Government proposed reforms to the scheme reducing some tariffs and increasing uncertainty over availability of the incentives in an attempt to keep the incentive scheme within budget (DECC, 2016a). For the RHI, biomass boilers are required to meet air quality requirements for the level of particulate matter (PM) and oxides of nitrogen (NOx) emissions of 30g/GJ net heat input and 150g/GJ net heat input respectively (Ofgem, 2013). The RHI cannot be claimed for biomass CHP if the CHP unit is already receiving the higher ROC level due to being CHP (DECC, 2015f). In response to perceived over-payments of RHI to low efficiency biomass CHP plants, Ofgem introduced scaling back of RHI payments for CHPs achieving less than 20% electrical efficiency (Ofgem, 2016).

Contracts for Difference (CfDs) and Capacity Market

The CfD scheme for CHP units will replace the Renewable Obligation from March 2017 and is available for units commissioned from 2015. Under the CfD contracts, a fixed price determined through an auction is given for the electricity produced. These CfDs are offered on a competitive basis in auctions to achieve lower guaranteed prices (DECC, 2015e) but some power generators may miss out of getting a contract. New biomass and energy from waste plants will only be supported if they are CHP power stations (DECC, 2013o). In the new CfD arrangements, Energy from Waste CHP can apply for either CfD or RHI support, while the other renewable CHP technologies can apply for both aspects (DECC, 2014g). The CHP power stations will be paid according to their qualifying power output in accordance with CHPQA definitions rather than the total power output under the CfD scheme (DECC, 2014d).

The UK's new Capacity Market is designed to ensure there will be enough generation capacity to meet peak demand (DECC, 2013f) and some DH CHP operators have applied to be part of it in 2018 (National Grid, 2014). Power plants cannot receive Capacity Market payments if they are also receiving CfDs, the RHI, or the Renewable Obligation, or if they hold long-term contracts to provide Short Term Operating Reserve (DECC, 2014i). It is more likely that non-renewable CHP plants will apply. Capacity below 2MW can participate in a Demand Side Response aggregation service (DECC, 2013n).

Feed in Tariffs (FiTs)

Anaerobic digesters are supported under the FiT scheme but the maximum capacity to be supported is due to drop from 5 MW to 500 kW under government proposals published in May 2016 (DECC, 2016b). Non-renewable domestic scale CHP units are supported provided their capacity is below 2kW electrical output (DECC, 2015f), however only 501 of these had registered for the FiT by the end of 2015 (DECC, 2016b).

3.4.5 Carbon price and other environmental legislation costs

There are policy incentives in the UK driving improvements in environmental performance, comprising four main elements: EU Emissions Trading System; Climate Change Levy; Climate Change Agreements; and the Carbon Reduction Commitment (DECC, 2013i).

European Union's Emissions Trading System (EU ETS) and Carbon Price Support (CPS)

The EUETS covers industrial and power station emissions and sets an emissions budget that declines over time. Qualifying emitters need to purchase allowances in order to fully cover their emissions, and these can be bought from companies with energy saving schemes or from companies that have emitted less than their allowance (European Commission, 2015).

Gas boiler use in heat networks is subject to charges under the EU ETS while individuals using gas for domestic boilers are not (DECC, 2013i). In the UK, the Carbon Price Support (CPS) scheme applies to fossil fuels for power generation and was designed to give more certainty over the carbon price in response to large fluctuations in the EU ETS allowance price. This UK-only measure increases the cost of carbon emissions. From 2015, fossil-fuel CHP units will be exempt from the CPS for the fuel used to generate electricity used on site (HMRC, 2014).

Figure 3-16 shows the projected changes in carbon cost for electricity suppliers and the industry and services covered by the EU ETS. The underlying assumptions for DECC's cost of carbon projections include a "fully functioning and comprehensive global carbon market in 2030" with long term carbon value trends consistent with UNFCCC goals of limiting global temperature increases to 2 °C above pre-industrial levels (DECC, 2014n). The ETI suggest that the transition to low-carbon infrastructure could be financed with a carbon price of £150 per tonne by 2030 rising to £250 per tonne by 2050, with zero emission vehicles requiring a carbon price of £250 per tonne (ETI, 2015). Recent EUETS reforms are expected to raise the price to around €30 in 2030 (in 2014 price terms, Energy Institute, 2015). Price projections are not necessarily consistent with current UK government and EU policy.

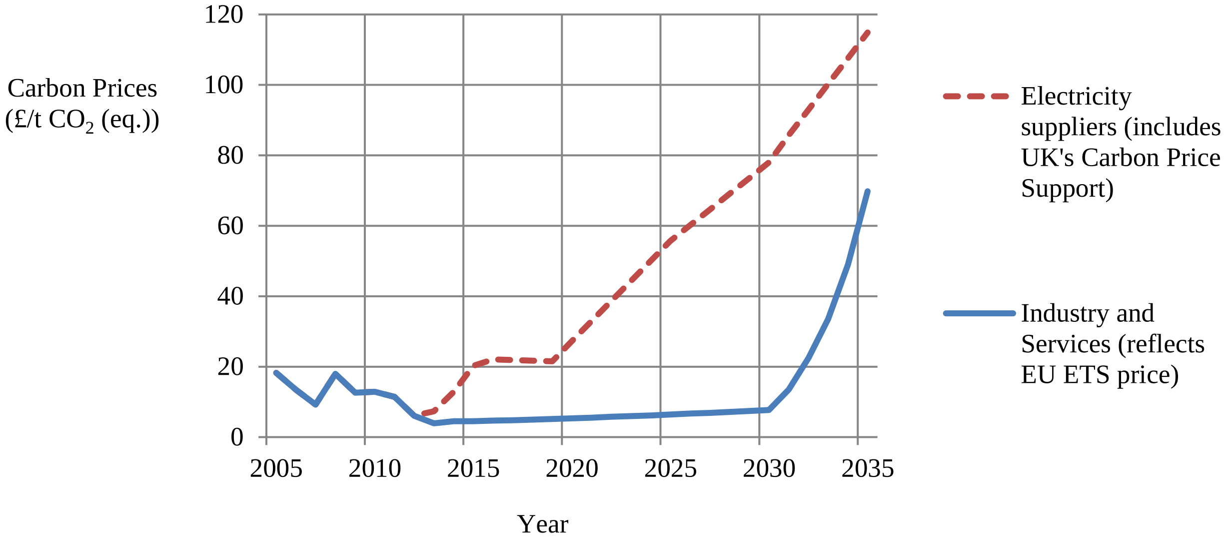

Figure 3-16: The projected changes in the cost of emitting a tonne of carbon dioxide.
Source: DECC (2014l).

Climate Change Levy (CCL) and Climate Change Agreements (CCAs)

The CCL is designed to encourage energy efficiency in industry, the commercial sector and the public sector. It adds cost to electricity, gas and fossil fuels used by industry, the commercial sector and the public sector. Exemptions from CCL act as an incentive for CHP units as detailed in Section 3.4.3. Energy-intensive industries can qualify for a 65% discount on CCL for gas and 90% on CCL for electricity by entering into a CCA (DECC, 2015) which includes energy efficiency targets (DECC, 2013i). If 70% of a site’s energy consumption is covered by a CCA, then the site is exempt from the Carbon Reduction Commitment (HM Treasury, 2015).

Carbon Reduction Commitment (CRC)

The CRC is for organisations whose emissions are not covered under Climate Change Agreements or the EU ETS (gov.uk, 2014). In Phase 1, the allowance price has been set at £12 per tonne of CO_2 equivalent emitted (*ibid.*). The forecast sales prices for carbon cost in 2014/15 and 2015/16 are £15.60 and £16.10 respectively (gov.uk, 2015c). The CRC is to be abolished in 2019 with an increased rate of Climate Change Levy to make up for loss of revenue with a greater proportional weighting onto gas in reflection of the reduction in carbon emissions associated with grid electricity (HM Treasury, 2016).

3.4.6 Capital Costs

The capital costs of a project can be divided into the “fixed capital” and the “working capital”. The fixed capital is the total cost of the plant ready to begin operation; the working capital is the investment required beyond the fixed capital in order to get the plant operational and gaining income (Coulson and Richardson, 1999b). The easiest way to gain realistic estimates of the capital costs is to look for cost figures for similar projects that have been completed recently. Recent information on the costs of building and operating heat networks was compiled by Element Energy for the UK’s Climate Change Committee (Element Energy, 2015).

Cost Indices

If recent cost figures cannot be found, then figures can be brought up to date using cost indices which detail the proportional changes over time in the cost of labour, materials and energy. These indices are found in government statistical digests and also in trade journals (Coulson and Richardson, 1999b). Composite indices may be appropriate; these take into account the variation of different types of costs and how they individually have changed, for example considering the changes of electrical engineering costs and civil engineering costs and others (*ibid.*). However, the use of such indices can introduce errors and so these should only be used when up-to-date data is not available.

Exchange Rates

Projects built in other countries can be used to gain estimates of the cost for a project in this country. Coulson and Richardson (1999b) recommend for historical costs abroad, to use the exchange rate of the time and then the UK cost indices since that time in order to bring the costs up to date. Historical exchange rate values can be found in the Government publication, *Economic Trends*. Where materials for projects are imported from abroad then the exchange rates will have a direct impact on project costs; contingencies for exchange rate movements are typically included in project costs.

Effect of Capacity

Economies of scale mean that an installation with double the capacity is unlikely to have double the capital costs. An indexed relationship of capital cost to capacity is given by Equation 3.43 (Coulson and Richardson, 1999b), where *S* is the capacity of the two scales of project, *C* is the capital cost of each scale and *n* is usually taken to have a value around 0.6 (*ibid.*).

$$C_2 = C_1 \left(\frac{S_2}{S_1}\right)^n \tag{3.43}$$

Capital Costs of Reciprocating Engine CHP units

Typical investment costs for a natural gas reciprocating engine CHP are around £844,000 per MW of installed electrical capacity for the range of 0.1 MW_e to 12 MW_e according to Element Energy (2015). Additional costs will be incurred as necessary for integrating the CHP with existing heat and power distribution systems and these will vary according to the nature of the site.

3.4.7 Operating Costs

Once an energy storage or CHP plant is operational, there will be costs associated with producing the product which can be divided into fixed costs, which do not vary with the production rate, and variable operating costs which do depend upon the amount of product produced. For long term investments such as DH and energy storage, the operating costs are key to the overall business case.

Estimated costs for raw materials can be gained from industry publications. Fuel costs were discussed in Section 3.4.1 and recent operational costs for DH were compiled by Element Energy (2015).

Operation and maintenance costs for CHP units are typically defined by CHP suppliers who offer maintenance contracts at a fixed rate per hour. The expected run regime for the reciprocating engine will in part determine the price and a high number of switch ons (i.e. more than one per day) could invalidate the warranty under that maintenance contract. Frequent starting and stopping is not recommended for CHP engines as it shortens their operational lives. A minimum running time of 3 hours and a cost €8/switch per MW is the cost used by Streckiene and Andersen (2008). The cost of operation and maintenance contracts depend on the running regime of the engine. Element Energy (2015) estimate this cost as approximately £68,000 per MW of electrical capacity for CHP units from 0.1 to 12 MW_e. Fragaki et al (2008) study the benefits of using gas CHP with storage showing significant benefits in terms of return on investment. They use information including retail price signals in the UK and Table 3-6 details some of their assumptions. Since Fragaki et al.'s publication there have been significant rises of retail gas and electricity prices and the Climate Change Levy exemption for electricity sold to grid from a CHP has been withdrawn.

Table 3-6: Economic parameters used by Fragaki et al (2008) to assess gas-fired CHP with storage in the UK.

Gas Cost	£18.9 /MWh
Climate Change Levy	£1.5 /MWh
Engine O&M Cost	£6-7 /MWh
Boilers annual O&M costs	£2500
Heat Sale price	£25 /MWh
Electricity sale price	Variable tariffs; £30-68 /MWh
Investment cost of 1 MW engine	£500,000
Investment cost of thermal store	£714 /m^3
Lifetime of the investments	15 years
Discount Rate	5 %

3.4.8 Modelling Investments

There are numerous ways to evaluate the effectiveness of investments. The simple payback time (PBT) is given by Equations 3.44 and 3.45. The Net Present Value (NPV) takes account of discounted cash flows for future years in order to represent the risk of changes that affect that future income as well as the higher value of income that can be used immediately; the public sector discount rate of 3.5% per year is recommended by the UK Treasury Green Book (HM Treasury, 2011). Internal Rate of Return (IRR) is yet another measure, being the discount rate required to produce a present value of zero (*ibid.*).

$$\text{PBT} = \text{investment cost} \,/\, \text{annual saving} \tag{3.44}$$

$$\text{PBT} = \text{investment cost} \,/(\, \text{revenue - operating cost}) \tag{3.45}$$

For a DH network, the capital costs are recouped through the charges for the heat, and in some instances also through incentives applied for operation of power generation in combined heat and power mode. Persson and Werner (2011) developed the concept of a capital heat distribution cost, C_d, in £/GJ as in Equation 3.46, where *a* is the annuity factor that recuperates the interest over the duration of the project, *I* is the investment cost and Q_s is the heat sold per year (in GJ/a).

$$C_d = \frac{\alpha . I}{Q_s} \tag{3.46}$$

In order to generate a profit, the cost of the heat and the cost of electricity sold will include enough revenue to cover the power station's fuel costs and running costs. For a waste heat recovery plant, heat pump, or heat-only energy centre, there is likely to be no electricity sold and there may in fact be electricity consumed by a heat pump to raise the temperature of the 'waste' heat.

3.4.9 Water Store Costs

For water store costs there are some estimates in the literature as well as specific figures based on previous projects; some examples are listed in Table 3-7 with equivalent costs in £/m^3 plotted in Figure 3-17. Table 3-8 shows the break-down of costs for a tank thermal store from an IEA study.

Table 3-7: Costs for hot water storage at various scales of applicaiton.
1 GBP = 8.7108 DKK = 1.1715 EUR = 1.2357 USD (HMRC, 2016)

Scale	Capital Cost	Converted Cost (£/m^3)	Notes	Source
-	1700DKK/m^3	195		Lund and Andersen (2005)
-	€3/kWh		Also €0.1/kWh delivered	Hadorn et al. (2007)
-	€268/m^3	229		Streckiene and Andersen (2008)
-	£1000/m^3	1000	Industry estimate for UK	Martin and Thornley (2013)
1 m^3	€1000/m^3	854		Faninger (1998)
70 m^3	£714/m^3	714		Fragaki et al. (2008)
300 m^3	£390/m^3	390		Eames et al. (2014)
300 m^3	£1070/m^3	1070	£320,000 for a 300m^3 store.	Warwick University (2016, 2016b).
1,000 m^3	$120/m^3	97	1980 UK price for steel tank	IEA (1983)
1,000 m^3	€2400/m^3	2049	Total cost for pressure vessel in Italy	Verda and Colella (2011)
4,000 m^3	€87/m^3	74	Insulated steel tank example in Denmark	Ellehauge and Pedersen (2007)
10,000 m^3	$100/m^3	81	1980 UK price for steel tank	IEA (1983)
10,000 m^3	€40/m^3	34	Earth pit	Faninger (1998)
10,000 m^3	€87/m^3	74	Pit storage example in Denmark	Ellehauge and Pedersen (2007)
40,000 m^3	$63/m^3	51	1981 Swedish steel tank for DH (total investment cost)	IEA (1983)
75,000 m^3	£25/m^3	25		Eames et al. (2014)
100,000 m^3	€10/m^3	9	Rock cavern	Faninger (1998)

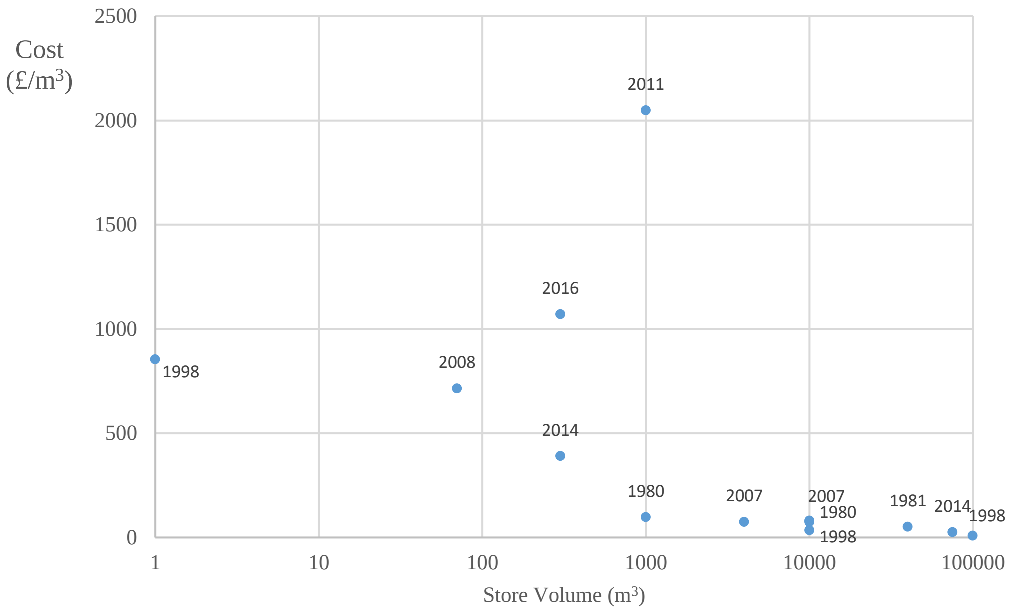

Figure 3-17: Hot water store costs versus volume (year of cost shown on labels).

Table 3-8: Distribution of costs for steel tank installed for daily use in Stockholm's DH system. Source: IEA (1983).

Item	Percentage of cost (%)
Tank	40
Foundation	12
Insulation (300mm)	12
Tubing, valves, pumps	28
Design and control	8

3.5 Choice of Storage Technology

The most obvious choice of storage technology for a heat network is to store the heat transfer fluid itself; this approach minimises the degree of adaptation required for the case study heat network. Advantages of hot water buffer vessels include a low cost and non-toxic medium with high specific heat capacity. The fact that the heat storage and heat transfer fluids are then the same means there are no heat transfers between materials and so the associated temperature drops are avoided. Many other technologies have however been considered in the Literature Review and it is important to consider their potential applications.

The potential for storage at lower cost using an alternative technology has been excluded. Water has a high heat capacity and low cost. Hauer (2013) reinforced this opinion, finding that water sensible stores are significantly cheaper per kilowatt-hour stored than phase change materials and chemical reactions as given in Table 3-9.

Table 3-9: The estimated costs of storage systems per kWh of storage capacity.
Source: Hauer (2013).

Technology	Costs (€/kWh)
Sensible (hot water)	0.1-10
Phase Change Material	10-50
Chemical Reactions	8-100

Some sensible materials are low cost and could serve applications that liquid water cannot, such as ceramics or concrete at high temperatures as featured in Section 2.4.1. High temperature applications could be implemented at industrial or power generation sites; this thesis is interested in the modes of operation which link to the heat networks. At a steam turbine CHP, minimising the temperature of heat draw-off is key to maintaining efficiency, as described in Section 3.1.4, and then it could be transferred to a high temperature material and then to the DH water. The additional heat exchangers and temperature drops associated with charging and discharging the material are expected to have a significant system efficiency effect and therefore this option has been rejected. In the steelworks case study of Chapter 5, steam accumulators are used to manage some of the high temperature waste heat in order to feed some heat to steam processes on site rather than feeding heat to district heating.

Mid- to high-temperature phase change materials could fit applications at the heat source as described above, with an additional advantage of high heat capacity over a narrow temperature band. This helps to minimise the cost of storage material as well as the thermodynamic penalty for temperature drops. To this end, erythritol was considered in particular. This PCM has the advantage of relatively low cost as it is manufactured as a food additive and its phase change temperature is slightly above the supply temperature of the Sheffield heat network. Experimental experience with erythritol was reviewed in Secition 2.5.2 and it was found that a large gap was necessary between the temperature of the charging fluid and the discharging fluid in order to overcome low conductivities and enable the phase change. For this reason, the use of erythritol and other phase change materials was rejected.

Low temperature storage is another option, with the chapeast being the use of thermal inertia already in the buidlings as discussed in Section 2.6.3. Judging the effectiveness of such a proposal is beyond the scope of this work. For example, the increased temperature may have an unintended consequence in terms of greater usage of circulation fans leading to unwanted increase in electrical consumption or greater opening of windows and therefore heat loss. Alternative storage technologies such as borehole thermal stores have advantage in achieving large capacity of storage for relatively low cost. Such systems could have application if there is benefit in storing large amounts of heat between summer and winter. By contrast in this case study, short term heat storage (within a day or a few days) is the dominant driver for an optimised energy system. The assessment of ground conditions is a risk to any developer of such an installation. One of the main limitations is that the ground can only be reasonably heated to 65 to 90°C, depending upon the nature of the ground and other factors. Thus a heat pump is likely to be needed to recover this heat and provide sufficiently high temperatures as required by the buildings.

Finally, considering that the primary sources of heat for the network are combined heat and power plants, it is worth considering the cost of electricity storage. At the start of 2015, Wood et al (2015) noted a current price for lithium ion-batteries of \$503/kWh capacity with possible reductions to \$370/kWh with some future manufacturing process changes. These costs are an order of magnitude or two more than hot water storage which equally offers flexibility to the CHP operation patterns and electricity storage offers no advantage when for example waste heat production from industry exceeds network heat demand.

3.6 Environmental Analysis

The use of gas, electricity and DH heat all have environmental impacts including the use of natural resources and the emission of pollutants into the atmosphere during their production. Particulate matter and oxides of nitrogen are of particular concern at a local level in terms of air quality effects while the emission of carbon dioxide and other greenhouse gases to atmosphere has a more dispersed effect.

The UK Department of Environment, Food and Rural Affairs (DEFRA) provides organisations with guidance upon measuring and reporting their own greenhouse gas emissions, publishing greenhouse gas emission factors for various types of energy use, including burning fuel as well as for the use of combined heat and power (DEFRA, 2012). An organisation does not need to separately allocate emissions from CHP to produced heat and power unless some heat or power is sold to another organisation (DEFRA, 2013a).

3.6.1 Emissions from fuel consumption

The emissions factors for various relevant fuels are given in Table 3-10; Scope 1 emissions reflect those emissions of greenhouse gases produced from combustion while Scope 3 includes those associated with extraction, refining and transport of the fuels (Gov.uk, 2013g). For solid biomass, the combustion carbon emissions are assumed to be captured in the plant growth process (in line with EU Renewable

Energy Directive methodology) and pre-combustion emissions for transport and processing of around 20 kg CO_2 equivalent per MWh of thermal content is estimated by DNV GL as applicable (DECC, 2015b); figures for this contribution assessed by the Government are included in Table 3-10.

Table 3-10: Emission factors for fuels.
Source: Gov.uk (2013g).

	Scope 1 (kgCO_2(eq)/kWh)	Scope 3 (kgCO_2(eq)/kWh)	Total emissions (kgCO_2(eq)/kWh)
Natural Gas	0.18521	0.01914	0.20435
Fuel Oil	0.26826	0.05059	0.31885
Wood Chips	-	0.01579	0.01579

3.6.2 Emissions from heat consumption

The government produces annual average emissions factors for heat and steam supplied via district heating reflecting the national fuel mix but for individual schemes, scheme-specific carbon factors should be used (DEFRA, 2016). In 2012, Sheffield's city centre district energy system delivered heat with an average carbon intensity factor of 0.137 kg CO_2/kWh (ARUP, 2012). The evaluation of the emissions factors for heat from the district heating system is complicated due to the life cycle assessment of waste disposal and is beyond the scope of this study. The emissions factor for the city-centre network is assumed to be 0.137 kg CO_2/kWh and for the Lower Don Valley network the carbon savings are calculated based on a counterfactual calculated use of gas boilers in the DH network only as the biomass is considered to carry no emissions.

3.6.3 Emissions from distribution losses

For DH-connected businesses, emissions associated with distribution losses are classed as Scope 3 under the GHG Protocol (DEFRA, 2012), and thus need only be included where a company is measuring its Scope 3 emissions. In the UK government methodology, an extra 5% is added to the carbon footprint to allow for typical network losses with DH (*ibid.*), however in this thesis a specific analysis of the losses is developed.

3.6.4 Emissions from power exchange with the national grid

When power is added to the national grid, the environmental impact can be assessed using the Marginal Emission Factor which represents the emissions factor of the power producer which is required to produce less electricity to balance the system. A study by LCP and Enappsys (2014) looked at the data for the marginal plants in the electricity market over four years and evaluated these marginal emission factors using three distinct approaches. Figure 3-18 shows how the value of marginal emission factor (averaged over all settlement periods) fell to a range of 400-550 kg CO_2/MWh in 2013. Further, one of the calculation methods for marginal plants highlighted that this trend may represent a change from coal to gas as the marginal plant as a result of fuel price movement (LCP and Enappsys, 2014).

Future changes to the MEF were explored in models produced by DECC to understand the impact of bespoke gas CHP policy (DECC, 2014j); these models account for a changing MEF as the UK's generation mix changes to include increased levels of renewable and low carbon (including carbon capture and storage and nuclear) generation deployment. The MEF for a gas CHP is calculated depending on whether the CHP responds to retail price signals (for example, a large energy user using CHP to reduce electrical import volumes during high price periods) or in the case of a generator that exports the majority of its output and is influenced by the spot prices then the electricity production pattern will differ.

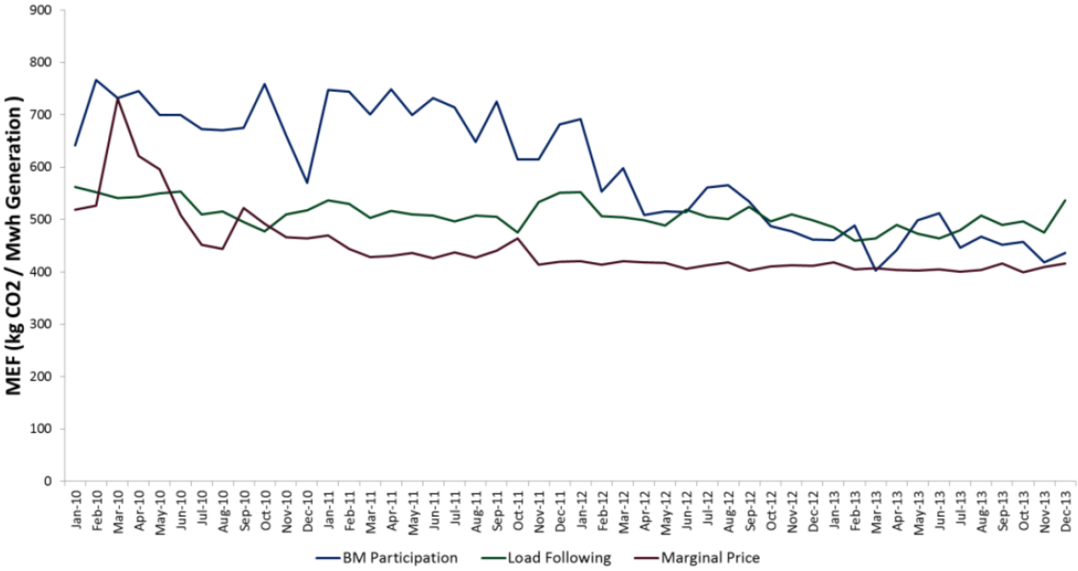

Figure 3-18: The marginal emission factor for UK grid electricity calculated using three separate methods. Source: LCP and Enappsys (2014).

The projected time series for 'on-site' consumption (following retail price signals) and 'export' (following wholesale price signals) are shown in Figure 3-19. These MEF projections for 'on site' and 'export' over future years show initially a greater carbon reduction for on-site electricity consumption due to coal operating at low prices at the electricity generation market; in the future, it is increasingly renewables being curtailed at the margin during low price periods and hence the carbon saving of generation is reduced.

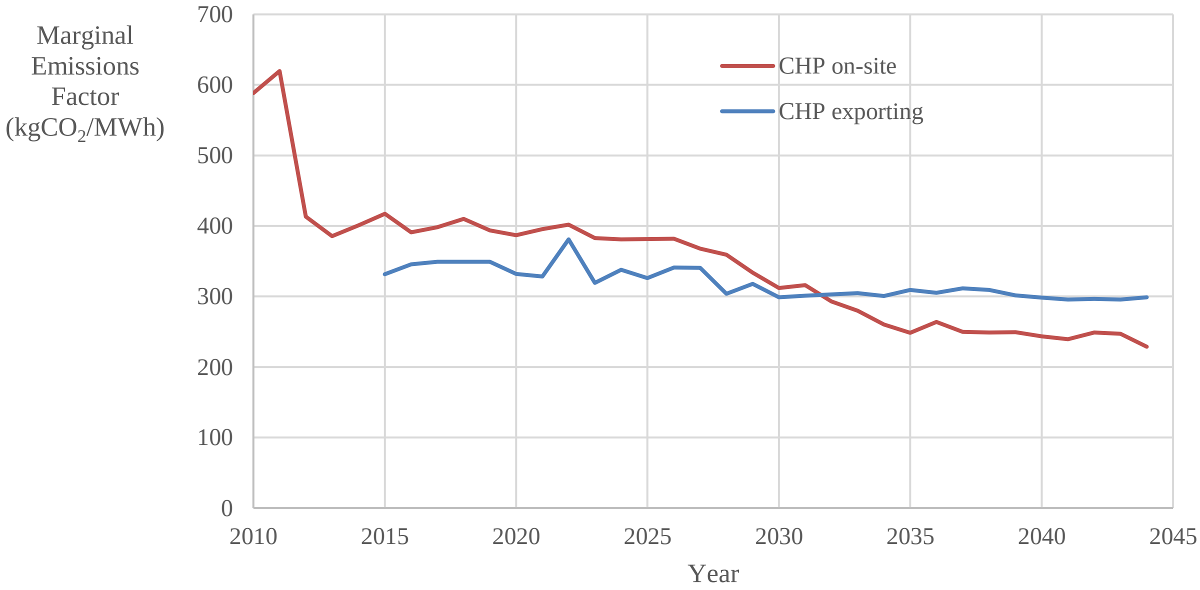

Figure 3-19: Modelled changes to the MEF for gas fired CHP operating under retail and wholesale price signals. Source: DECC (2014j).

The overall grid emissions factor in future, which reflects the national mixture of electricity generation, is expected to fall as more low-carbon electricity generation capacity is built in the UK. A range of actual and forecast grid carbon intensity factors is given in Table 3-11.

Table 3-11: Forecast and actual grid average carbon intensity factors.

Year	Value (gCO_2(eq.)/kWh)	Status	Notes	Source
2012	494 (generation) 43 (losses) 537 total	Actual, grid average factor.		DEFRA (2014b).
2013	462 (generation) 38 (losses) 500 total	Actual, grid average factor.		DECC (2015g).
2014	412 (generation) 37 (losses) 449 total	Actual, grid average factor.		DECC (2016d).
2015	417 (on site) 331 (export)	Forecast, CHP marginal emissions factors.	Onsite CHPs influenced by retail price signals, Exporting CHPs influenced by wholesale prices.	DECC (2014j).
2030	100	Forecast, grid average factor.	UK Government expectation.	DECC (2014k).
2030	Up to 260	Forecast, grid average factor.	Based on possible continued running of coal plants	Gross et al. (2014).
2030 2030	100 200	Forecast, grid average factors.	'Current Trends' scenario. 'Challenging World' scenario.	DECC (2015b).
2030	312 (on site) 299 (export)	Forecast CHP marginal emissions factor.	Onsite CHPs influenced by retail prices, Exporting CHPs influenced by wholesale prices.	DECC (2014j).
2044	229 (on site) 299 (export)	Forecast CHP marginal emissions factors.	Onsite CHPs influenced by retail prices, Exporting CHPs influenced by wholesale prices.	DECC (2014j).
2050 2050	26 150	Forecast, grid average factors.	'Current Trends' scenario. 'Challenging World' scenario.	DECC (2015b).

There is a time-lag of two years before the emissions factors are published so 2015's factors for comparison will not be available until mid-2017. The relevant carbon factors used in case studies of this thesis are described in Table 3-12. In chapter 5, where the potential for using a heat pump is of particular interest, three grid average carbon intensity scenarios are considered: 449g, 260g, and 100g CO_2(eq.)/kWh, with a pessimistic 260g in 2030 based on the analysis of Gross et al. (2014). The actual loss factors will vary geographically, the prediction of marginal emissions factor for the CHPs is also dependent on the running pattern, and the presence of some distribution-connected generation means that the exact grid factor will always be subject to some uncertainty.

Table 3-12: Grid carbon emission factors used in each case study.

Application	Emissions Factor Approach Applied	Factor Used
Chapter 4 – CHP use on site	2015 on site CHP predicted marginal emissions factor (417g) with 35g allowance for losses on avoided import.	417 + 35 = 452g/kWh
Chapter 5 – large CHP export	2015 exporting CHP predicted marginal emissions factor (331g), no losses benefit for exported power.	331 g/kWh
Chapter 5 – heat pump	2014 grid average factors (449g), including losses on power import.	449 g/kWh
Chapter 6 – large CHP export	2015 exporting CHP predicted marginal emissions factor (331g), no losses benefit for exported power.	331 g/kWh

3.7 Modelling Objectives and Implementation

Modelling approaches undertaken in prior research were reviewed in Section 2.3. Commercial packages such as EnergyPRO or TERMIS could have been used for this research, however the evolving nature of the study meant that the modelling flexibility required to analyse and understand the data set during the earlier stages naturally led to the use of Microsoft Excel for developing early modelling regarding implementation of CHP on a campus. The later analysis considering interaction of heat sources, heat storage and district heating was more suited to developing a bespoke model that could be run on the University of Sheffield's high performance computing facilities; this allowed for the quick and automated variation of different parameters to understand their effect of on an increasingly complex model.

The model's key objectives were:

- to show an accurate representation of the heat sources for the network, including the trade-offs between heat and power production where present and the varied nature of waste heat;
- to identify the appropriate scale of heat storage by demonstrating how system operation could be enhanced;
- to quantify the benefits of heat storage in terms of economic and carbon outcomes.

All models developed had to meet a specified heat demand for each half hour of the year by allowing for heat procution from various sources. The level of this heat demand varied between different case studies and different modelling scenarios. Availability functions are included as binary variables for each time period. Initial running allocations are done on the basis of heat load follow or electrical load follow modes as described in Section 2.3.3. Stepwise perturbation of CHP (heat and power) outputs away from this pattern through use of net heat production cost (NHPC) calculation to identify the most cost-effecitve timing of CHP use for thermal storage charging as decribed in Section 6.5.4. The optimal nature of the outcome cannot be proven mathematically due to non-linear factors in the calculation (as described in Section 2.3.3). The thorough testing of charge and discharge timings by the model algorithm through the course of a day as described in Section 5.4.8 gives confidence that the run patterns simulated are representative of a well-optimised system.

The first model, used for the University of Sheffield case study and detailed in Section 4.4.2, consisted of a Visual Basic algorithm within Microsoft Excel. This algorithm calculated run hours of the CHP units according to heat demand variations over time following an allocation algorithm. This model demonstrated heat store capacity required through performing an integration of heat rejected to the store. The carbon savings and financial savings were calculated post-hoc through a spreadsheet calculation.

The second model was built differently in order to reflect a limited store capacity and also to reflect half-hourly variation in electricity spot prices. Income from the electricity market was continually calculated as was the heat production cost from the various sources, however the overall electricity income including Renewable Obligation Certificates (ROCs) was calculated only at each year-end due to the dependence on annual system performance. Waste heat from industry had differing priority depending on whether the heat was recovered through a heat exchanger or via a heat pump. Heat from the CHP had a lower priority but always higher than the use of gas boilers. Commercial software such as EnergyPRO may have been able to perform parts of this modelling however the intensive computing load in terms of data inputs and outputs was better suited to computer code that could be easily automated over many simulations and input to the Universty of Sheffield's high performance computing facility.

The third model was adapted from the second but represented a major variation due to the introduction of a second CHP unit that is assumed to also be operating in the electricity spot market. The net heat production cost was calculated for each CHP in order to demonstrate how an interconnected system would operate with and without heat storage. Again, electricity spot market revenue was continually accrued, with the ROC revenues calculated annually based on overall system performance.

4 LOW-CARBON ENERGY FOR THE UNIVERSITY OF SHEFFIELD

4.1 Introduction

This chapter investigates the variations in heat demand of buildings at the University of Sheffield and investigates how combined heat and power (CHP) and heat storage can be applied to meet these energy demands. Consideration is given to the appropriate systems to meet that heat demand including the role that heat storage can play in reducing energy costs and environmental impact.

There are 1.8 million non-domestic buildings in the UK, responsible for 17% of the UK's energy consumption and by 2050, half of these buildings will still be in use (DECC, 2013i). Therefore this case study of retrofitting energy supply options to existing buildings is salient for national challenges of the UK and countries in a similar situation.

This case study concentrates on the main campus of the University of Sheffield where introduction of CHP technology is being considered to provide low carbon heat and electricity. Buildings in the campus are already connected to Sheffield's low-carbon city-wide heat network and so the challenges differ from previous case studies of CHP implementation in the UK. The network operation is investigated through analysis of diversity factors. The potential role of heat storage to fit with the existing heat network and act alongside the new CHP unit has been investigated. The approach and conclusions reached will be useful for other organisations considering implementing low-carbon energy solutions for buildings.

4.1.1 The University of Sheffield Energy Strategy

The University of Sheffield has ambitions to reduce its carbon dioxide emissions by 43% by 2020 against a 2005 baseline (ARUP, 2012). This target is expected to equate to a reduction of 19,000 tonnes of CO_2 equivalent per year by 2020 compared to business as usual (*ibid.*). The University's 2012 Energy Strategy includes reduction of energy consumption through building improvements, self-generation of energy, and lowering energy consumption through behavioural change of staff and students (*ibid.*).

It is self-generation of energy that would represent "by far the greatest carbon reduction" (*ibid.*). CHP units on site are judged by ARUP to have most potential if the existing heat network can be used as a sink for excess heat (*ibid.*). More than one CHP energy centre may be introduced, along with renewable fuel boilers at strategic locations, off-site wind turbines and building integrated solar panels. Purchase of renewable electricity from Sheffield's district energy operator was considered, but the costs of a physical private wire were prohibitive (University of Sheffield, 2013d).

The University spends over £8 million per year in providing power, heat and water to its facilities and these utility bills are likely to rise in future (University of Sheffield, 2013c). Introduction of CHP offers the opportunity to save money and carbon. The Energy Strategy considers how the future energy demands of the University are going to change and this is important when planning long-term investments in infrastructure. As of summer 2015, it appeared that a 2MW_e CHP and a biomass boiler would provide heat and power to buildings in the central part of the campus (University of Sheffield, 2015). Some examples of existing CHP use in UK universities are given in Table 2-9.

4.1.2 Existing supply of heat

The University of Sheffield currently uses heat supplied from Sheffield's city-centre heat network to heat 50 buildings (ARUP, 2012). The source for this heat is an Energy from Waste CHP power station and the heat supplied has a lower carbon emissions factor than using natural gas (*ibid.*). This lower impact is due to a biomass component in the waste and avoided greenhouse gas emissions caused by sending waste to landfill. The carbon emissions associated with each of the University's energy sources are listed in Table 4-1.

Table 4-1: Emissions factors for supplied energy.
Source: ARUP (2012).

Energy Type	Emissions Factor (kg CO_2(eq.)/ kWh)
Natural Gas	0.183
Heat Network (2012 figure)	0.137
Electricity	0.521

A small number of the University buildings still run on natural gas heating, including the halls of residence away from the main campus. Sometimes, due to flow dynamics in the heat network or a high demand level, gas and oil boilers on the University site are required to supplement the district heating (DH) supply. This boiler use increases the carbon dioxide emissions associated with heat and to alleviate this, using biomass boilers or hot water stores to top up the supply has also been discussed (ARUP, 2012). The emissions factor for heat from the heat network has been high in recent years because supplementary boilers were needed more than expected due to cold winters and unforeseen network and CHP plant outage (*ibid.*).

Figure 4-1 indicates the locations of all the buildings on the heat network and the University of Sheffield campus is circled. The boiler house at the University is labelled; this building contains back-up fossil fuel boilers and electrical pumps to maintain heat supply to all customers on the network.

Nearly all of the University buildings that are connected to the network have their own heat meters. The variation in the University's heat demand will be explored in Section 4.2 but it is instructive to look briefly at the network as a whole. Figure 4-2 shows the variability of heat demand over the course of a year for the whole network. The heat demand from University buildings makes up around a third of the demand, out of approximately 110,000 MWh delivered each year (12.6 MW average). The annual level of heat demand will vary according to weather conditions each year.

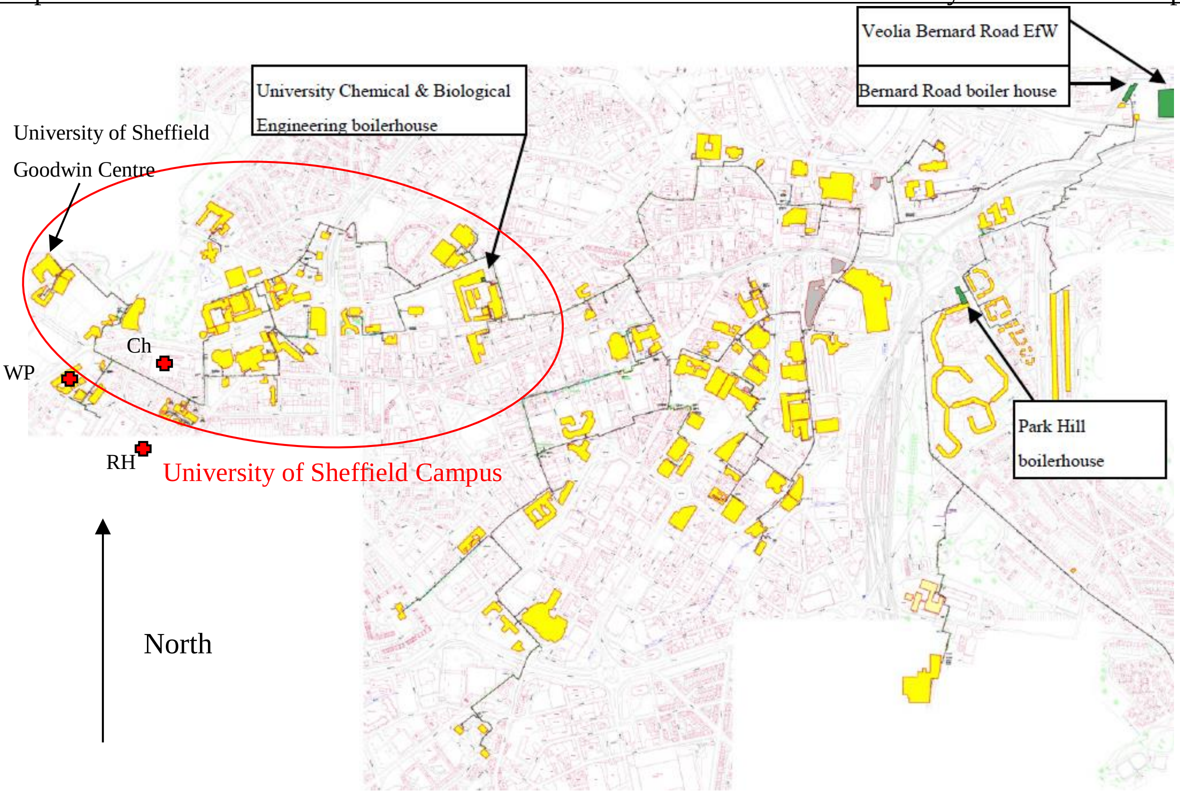

Figure 4-1: Sheffield city-centre heat network layout.
Red crosses label the Royal Hallamshire (RH), Weston Park (WP) and Children's (Ch) Hospitals. Source: ARUP (2012).

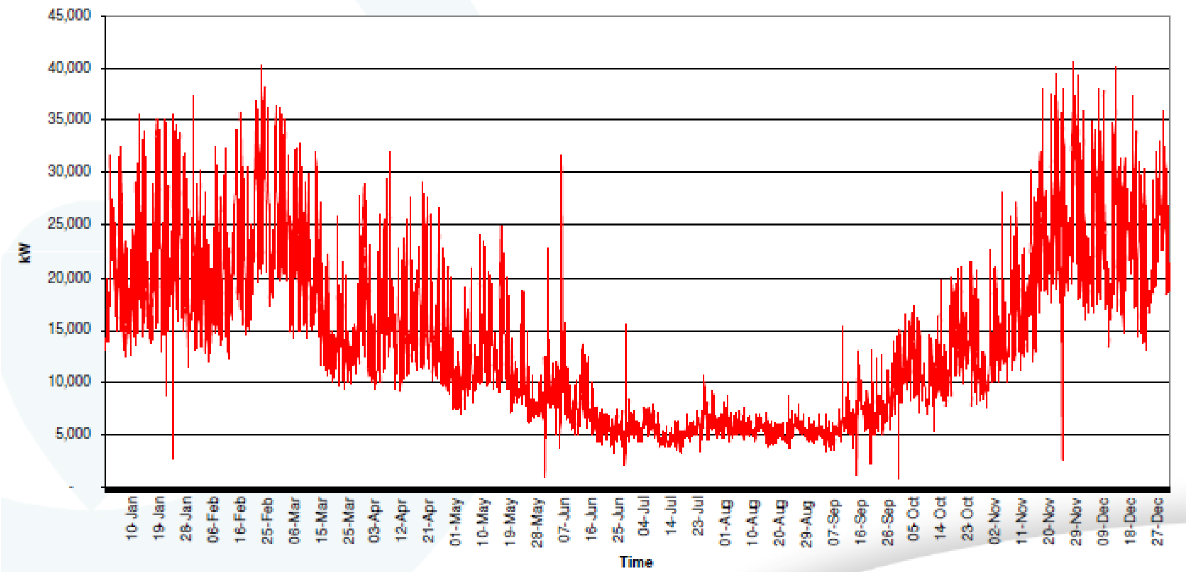

Figure 4-2: The total heat supply to the Sheffield's DH network in 2006 with half-hourly resolution.
Source: Veolia Environmental Services (2010).

Figure 4-2 shows that for the whole city-wide network the variability of demand is clear. This is both due to changing temperatures outdoors as well as variations in demand through the course of each day as the use of heating and hot water systems in buildings varies. The Energy Recovery Facility that supplies the heat runs a steam CHP turbine; when more heat is required by the heat network a greater amount of steam is bled off the turbine and condensed to provide that heat. A consequence of this bleeding of steam is that the electricity output falls meaning more electricity is produced at times of lower heat demand meaning greater electricity production during summer compared to winter and night compared to day.

Heat storage at the University could help achieve higher prices through shifting of electricity production timing. Weston Park Hospital (see Figure 4-1 for hospital locations) was considered for a heat accumulator previously but there is insufficient space there (Veolia Environmental Services, 2013b).

The CHP unit at the University would likely be a reciprocating engine type, working differently to the city-centre CHP in that the heat and electricity outputs from a small gas-fired engine are correlated rather than anti-correlated as for the turbine and with a limit on the turn-down of the gas engine CHP. Instead of condensing steam from a turbine, the CHP will supply hot water from its cooling system and possibly a waste heat boiler in the exhaust.

4.2 Characterising Heat Demand

4.2.1 Data resolution, completeness and quality

48 of the 50 buildings supplied with heating on campus have automatic metering capability (ARUP, 2012). 18 months of meter readings taken every half-hour running from May 2012 to November 2013 at individual building level were provided by the University of Sheffield Estates department for this study. The half-hourly average demand totalled across 31 buildings with full records is shown in Figure 4-3. Other heat meters had erroneous or missing readings for part of the period.

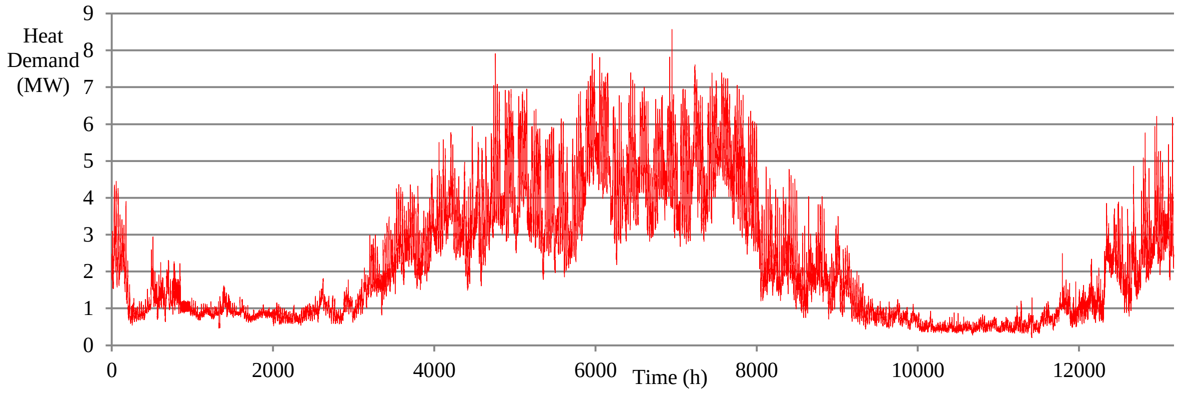

Figure 4-3: The full sequence of demand for 27 University of Sheffield buildings.
Note: 365 days = 8760 hours.

The buildings with a complete 18 month record are listed in Appendix 10.2 and these 31 buildings account for 24,267 MWh of demand per year. Another 23 buildings, listed in Appendix 10.2 have some missing data, including two buildings with completely missing records, and these buildings are estimated to consume 16,341 MWh per year. Therefore around 60 % of the University's total demand (40,608 MWh per year) is accounted for by complete records over 18 months.

4.2.2 Method for demand profile production

Where a focus on a 12 month period is required for modelling, the data from 1st July 2012 to 30th June 2013 is used during which a complete record of heat demand for 33 buildings is available. Addition of these buildings raised coverage to 66% of the total University of Sheffield demand. Figure 4-4 shows the variation of half-hourly demand readings from buildings that had full data for these 12 this is multiplied by a factor of approximately 1.5 to show expected demand for the whole campus.

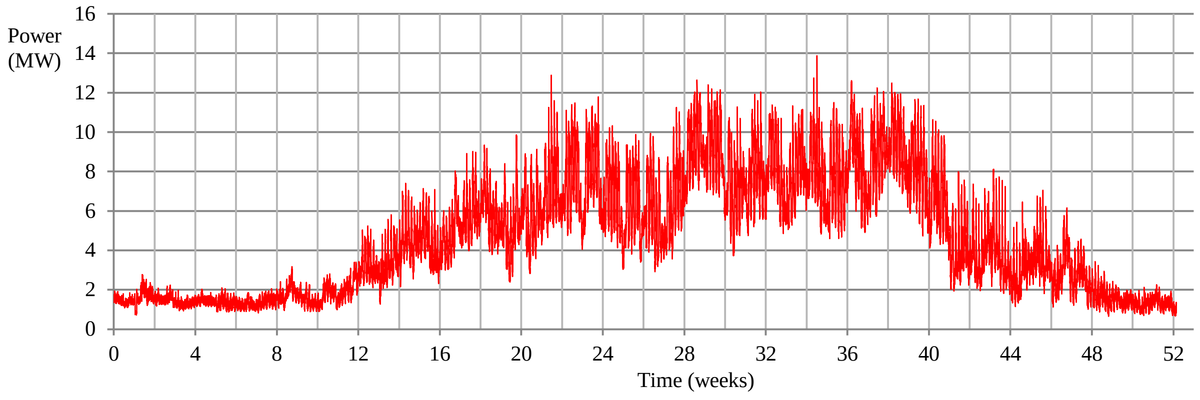

Figure 4-4: Half-hourly total heat demand for University buildings from July 2012 to June 2013.

There are meter readings every half hour and the rate of change of these readings is taken as the heat demand; this will lead to an under-representation of the short term variation of demand since any spikes are averaged over 30 minutes. Figure 4-5 shows the detail of this demand for the 33 buildings in December 2012 (upper curve) and July 2012 (lower curve). On the 8th July (Sunday), four of the sites where energy consumption is significant showed no demand and this may be due to servicing of heating systems, which would explain the reduction in demand. The weekly patterns of heat use in December are very clear.

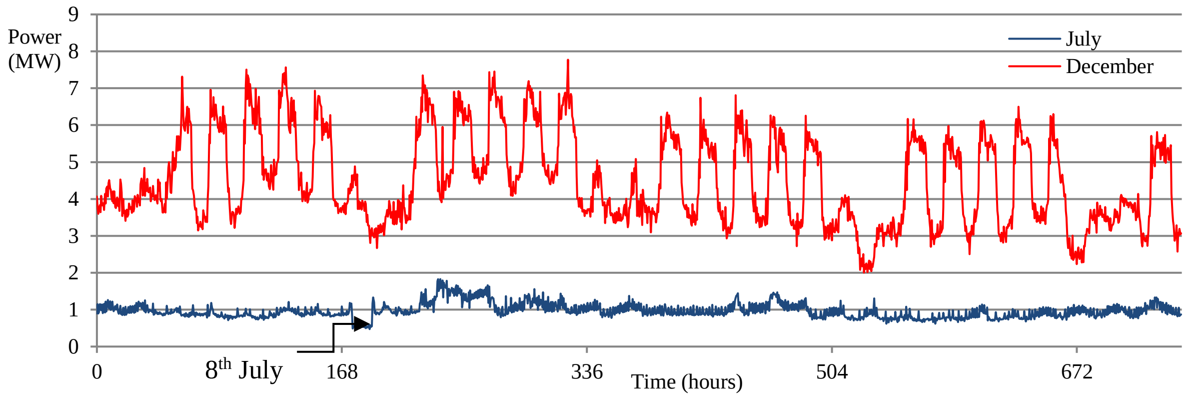

Figure 4-5: The demand variation through December 2012 and July 2012 for 29 University buildings.

It is clear from Figure 4-4 and Figure 4-5 that demand is strongly seasonal which will be due to outdoor temperature changes while the weekdays in winter have significantly higher loads than weekends do. Therefore the study of heat demand is split between the physical influences such as temperature and the social influences such as differences in building use between weekends and the days of the week.

4.2.3 Diversity of loads

With a collection of buildings, a network supplying heat (or power) can be sized smaller than the sum of peak demands as the chance of all building peak demands coinciding can be neglected; this effect was discussed in Section 3.2.2 and the building demand data from the University can be analysed to determine the diversity factor.

The algorithm created for the diversity analysis generates a random sequence into which the buildings are ordered. Then a second computer algorithm works out the peak heat demands for individual buildings and the peak for a collection of buildings. Some results of this analysis according to increasing numbers of buildings and increasing total demand are shown in Figure 4-6 to Figure 4-9. There are 33 buildings for which full records are available for a continuous 12 months and the period 1/7/2012 to 30/6/13 is used as the period of investigation.

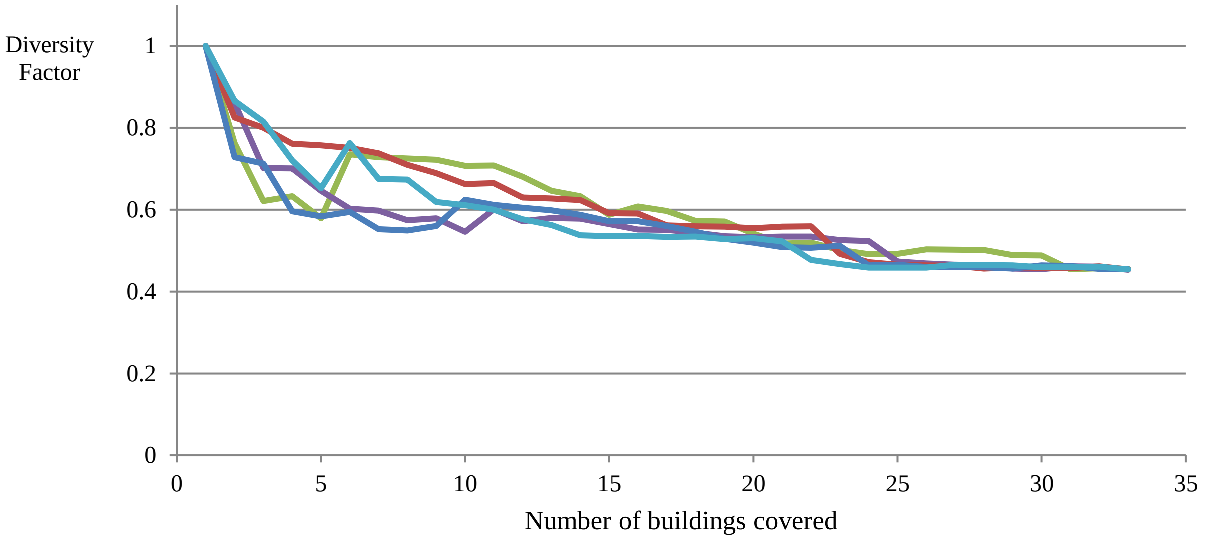

Figure 4-6: The build-up of buildings and the effect on diversity factor.

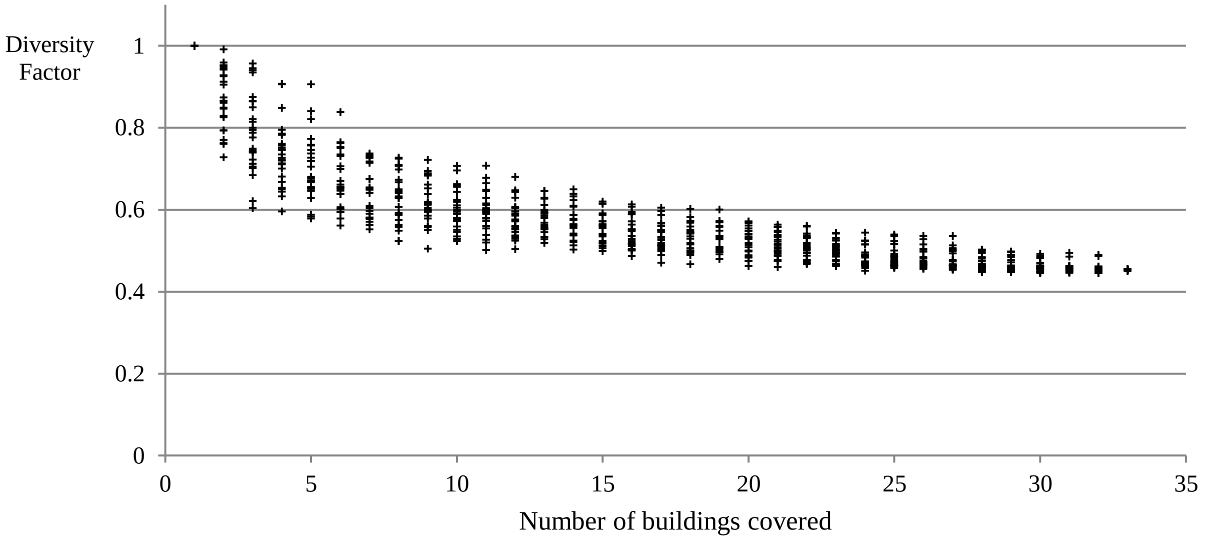

Figure 4-7: Variation of diversity factor with increasing numbers of buildings.

While Figure 4-6 and Figure 4-7 showed the variation according to increasing number of buildings, Figure 4-8 and Figure 4-9 show the variation according to the increasing level of demand.

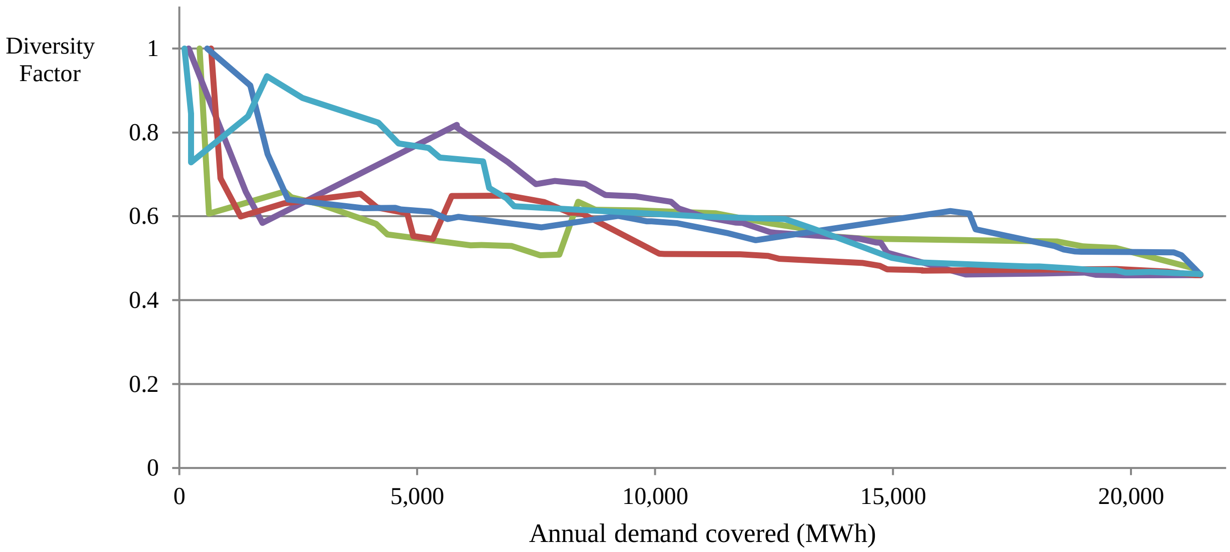

Figure 4-8: Variation of diversity with increasing collective demand.

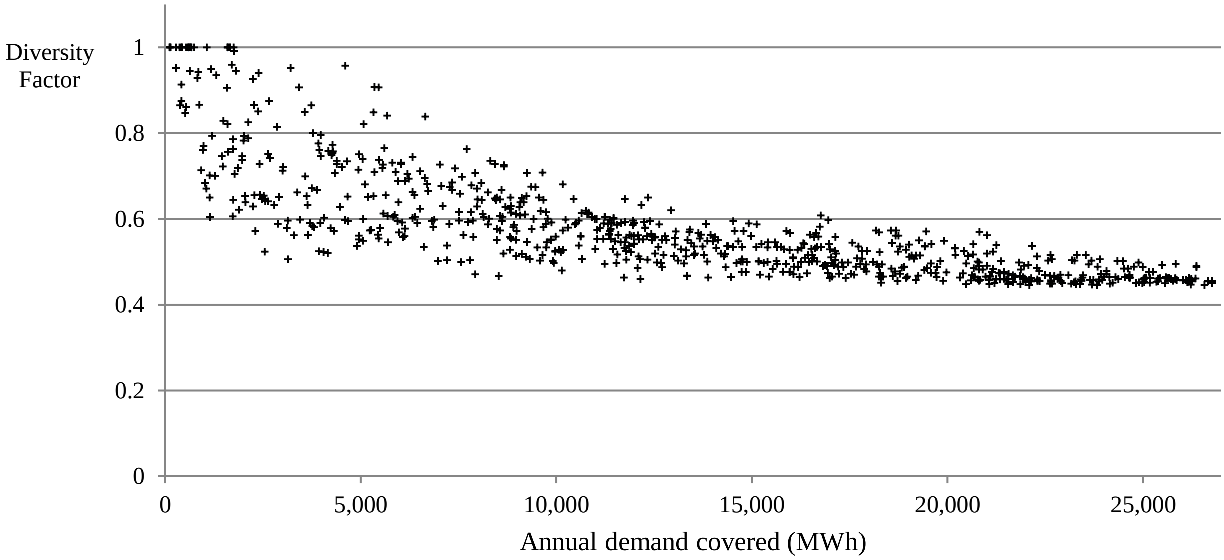

Figure 4-9: Diversity factors versus the total demand covered for different building combinations.

Comparison of Figure 4-7 and Figure 4-9 shows that increased number of buildings is a better indication of additional diversity than additional demand. If the University wishes to serve as much heat as possible to its own buildings then pipe heat distribution capacities mean that localised heat stores in locations where diversity is low can help reduce infrastructure spend.

Since these graphs refer to the same set of 33 buildings, once all the buildings are added in, the same total diversity factor will emerge, in other words all sequences of buildings tested converge on the same final point.

A cautious approach may conclude that a handful of buildings need to be connected via a particular branch before a diversity factor can be applied. For a specific set of buildings the characteristics of the building use as well as details of whether peaks emerge as a result of heating system control issues or from actual peak demand from heating systems should be considered.

Since the collective peak heat demand has been shown to be less than half the sum of individual peak demands (Diversity factor <0.5), it can be concluded that to cost effectively deploy a capacity of heat storage for the purpose of peak-shaving of heat demand benefits significantly from the connection of multiple buildings to a heat network. It does need to be borne in mind that the cost of such a network is very high but there are also other motives for doing so such as to exploit cheaper sources of heat and to reduce capacity of peaking boilers required.

4.3 Physical Influences on Heat Demand

4.3.1 Demand variation with external air temperatures

Heat consumption of buildings relates to external temperatures since the rate of heat loss will be higher when the drop in temperature between indoor and outdoor conditions is greater. This will be partly due to different rates of heat loss through the building fabric as well as a stronger heat loss when indoor and outdoor air is exchanged, for example when a door or window is opened. Research into a range of factors affecting variability of heat demand were reviewed in Section 2.3.1.

Hourly air temperature data from the weather station in Weston Park, adjacent to the university, was retrieved from the Centre for Environmental Data Analysis’s MIDAS dataset (CEDA, 2015). The temperature data and demand data are compared in Figure 4-10.

In Figure 4-10 there is a clear link between colder weather and weeks with higher demand and the weekly patterns of heat demand also occur independent of the weather conditions. The demand versus temperature plot is as shown in Figure 4-11. Since the temperature readings are hourly while the demand readings are half-hourly there are two demand readings for each temperature reading. The trend of higher demand in colder weather is clear, but there is also wide variation in demand seen even at times with similar temperatures demonstrating that heat demand is a function of other variables too.

When the demand level was studied at different times of the day and of the week, distinct patterns emerged. At the times of the highest temperatures, demand will come from the use of hot water, from year round heat needs such as the swimming pool, or perhaps from heat losses behind the heat meter. Figure 4-12 shows a subset of the data corresponding to six different times on Mondays. The evening and night time demand readings are lower than the average, as expected. Some of the 4 a.m. readings are among the highest representing heating of the building before occupancy.

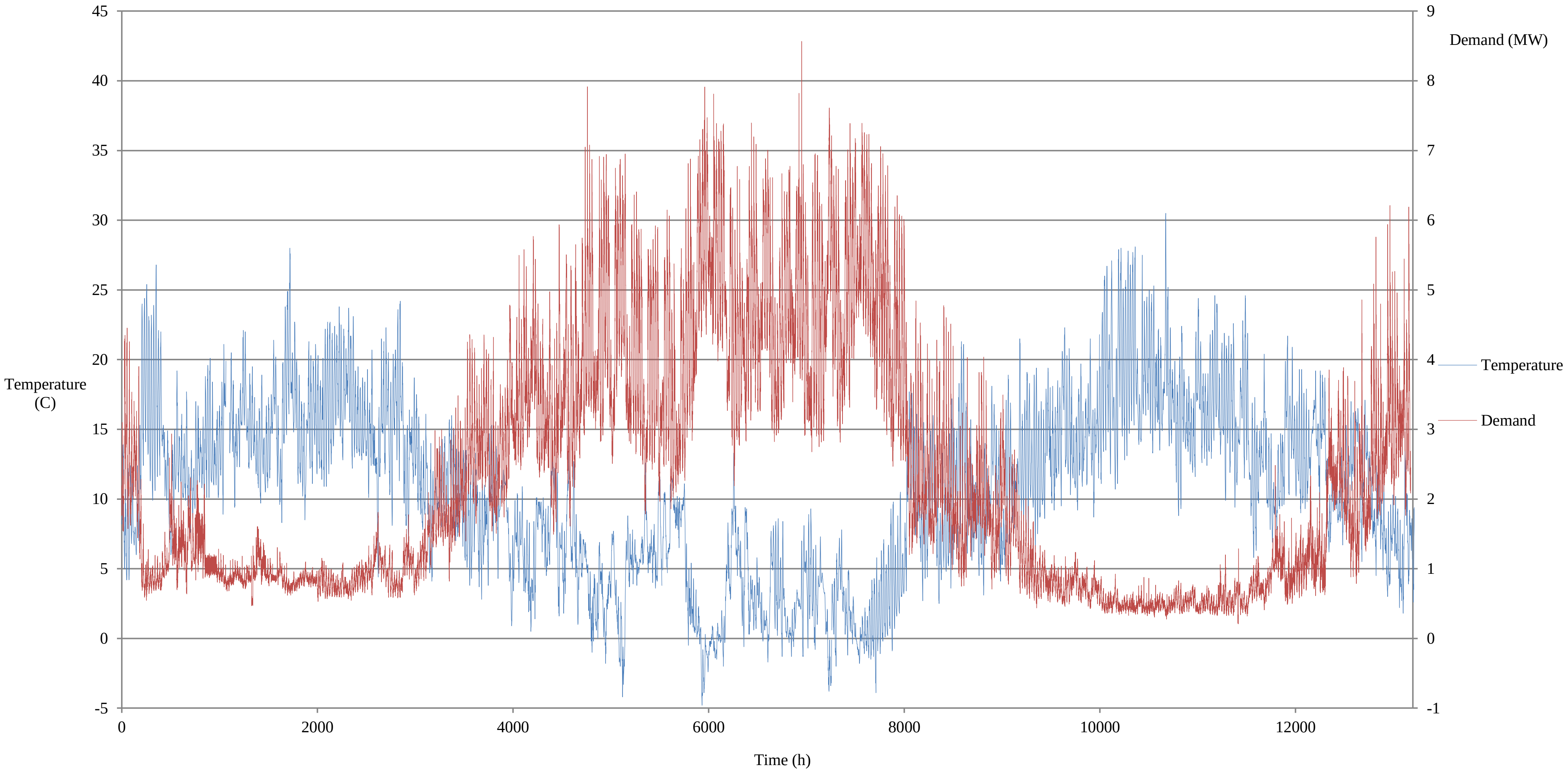

Figure 4-10: Hourly air temperature data for Sheffield compared with half hourly metered data for 31 buildings. Source: Temperature data from CEDA (2015), demand data from the University of Sheffield.

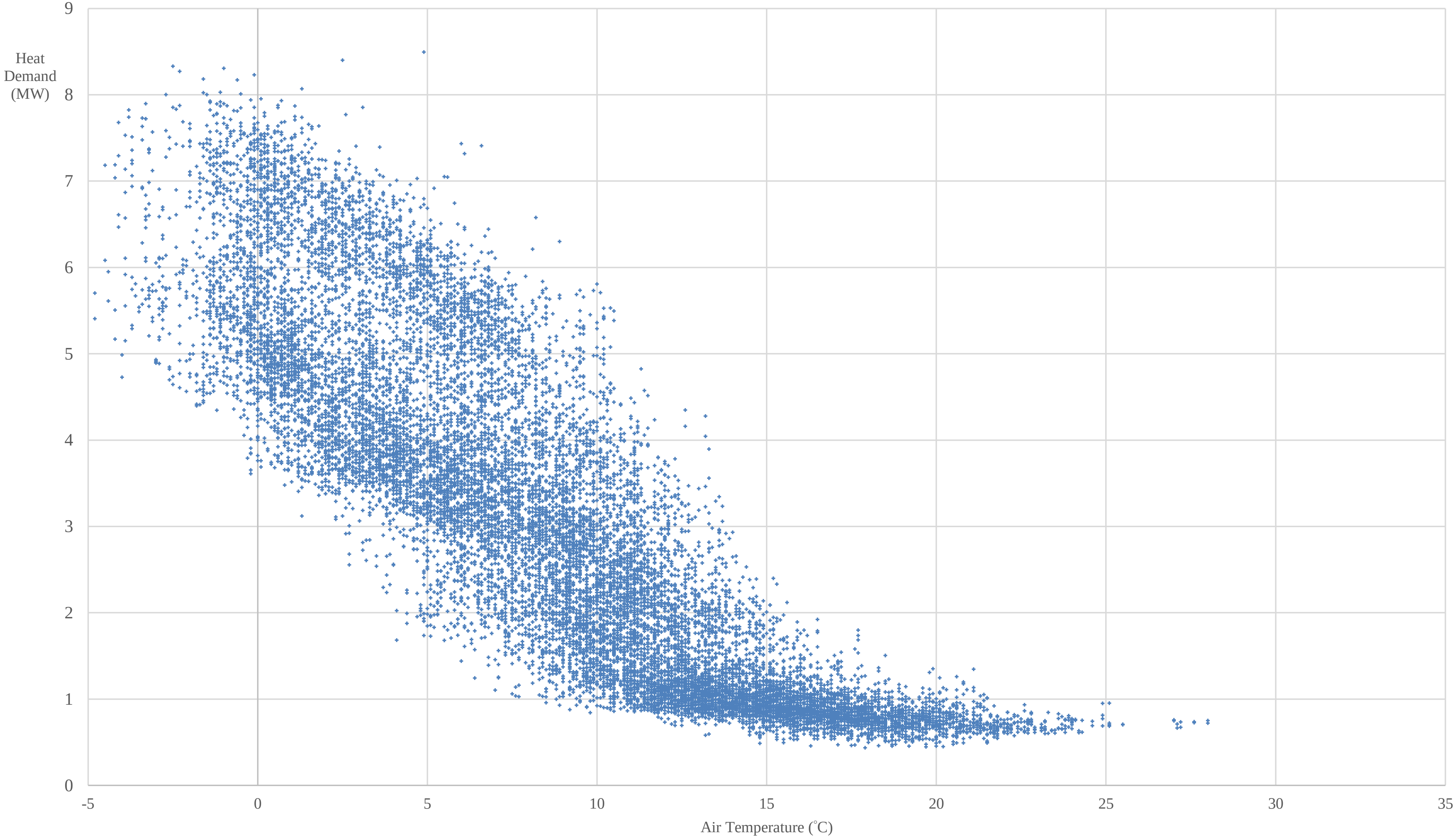

Figure 4-11: University of Sheffield heat demand for 33 buildings versus air temperature at each hour across 12 months.

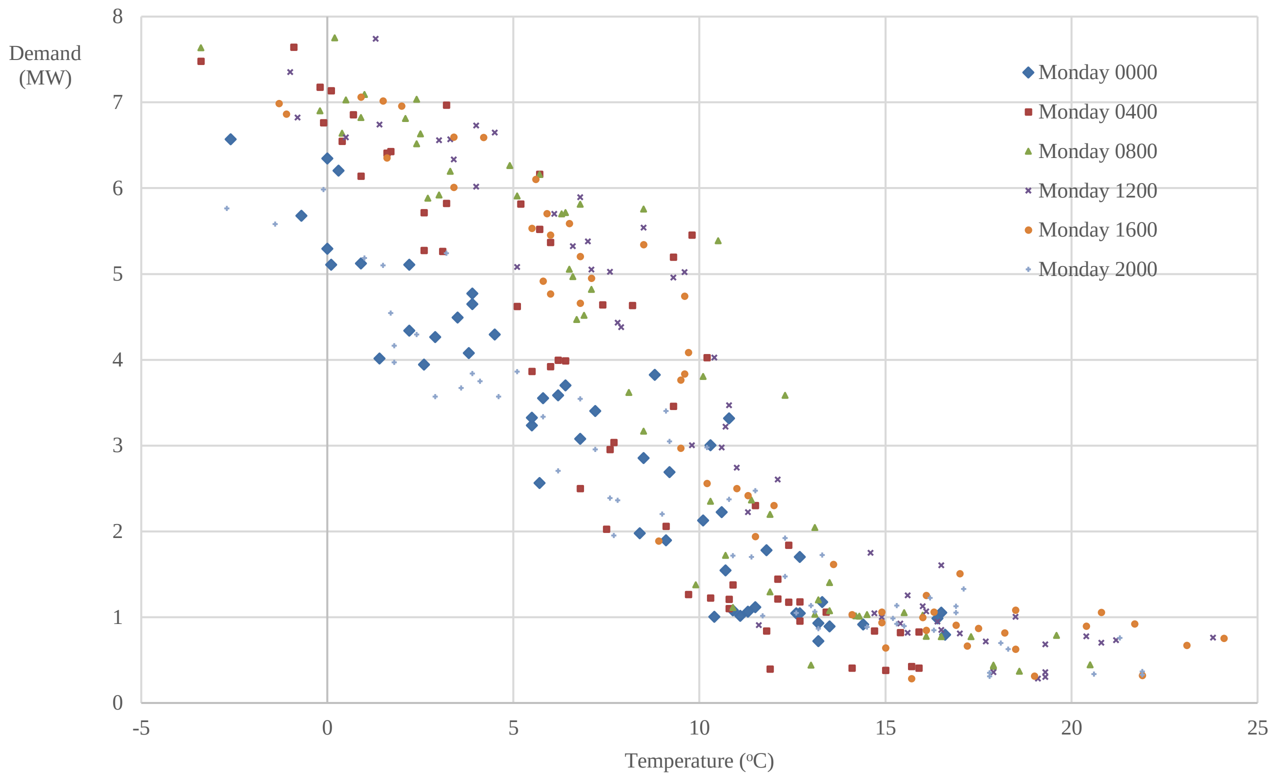

Figure 4-12: University of Sheffield heat demand versus air temperature at specific times on Mondays.

The scatter of these data points in Figure 4-12 helps to illustrate the uncertainty when making predictions of heat demand on the network even if the temperature has been well-forecast.

December, January, February and March stand out as the coldest months while June, July and August are clearly the warmest months and it's a variation of demand between those extremes that may be the most difficult to predict. Table 4-2 lists the recorded degree day figures each month and the 20-year averages for a nearby weather station at Bingley in West Yorkshire. March is particularly cold in the sample year.

Table 4-2: The monthly total and average degree day counts.
Note that the number of degree days seen in Bingley is sometimes much higher than the East Pennine numbers.
Source: Degree Days Direct Limited (2013).

Month	Degree Days	Average Day	20 year average (7/1993 to 6/2013)
March 2013	463	14.9	275
February 2013	389	13.9	300
January 2013	410	13.2	342
December 2012	377	12.2	349
November 2012	306	10.2	247
April 2013	298	9.9	269
October 2012	252	8.1	147
May 2013	207	6.7	133
September 2012	137	4.6	63
June 2013	102	3.4	66
July 2012	72	2.3	35
August 2012	55	1.8	31

4.3.2 Social influences on heat demand: daily routines

Heat demand varies according to temperature but also between night and day and between days of the week. The typical demand profiles through a week are presented in greater detail here in order to understand how a CHP engine could meet these varying demands and also what role that heat storage could play. Demand variation over the course of the day is largely caused by social behaviour such as the turning on of heating when people wake up in the morning as well as the movement of people to work meaning a greater heating requirement.

To illustrate the typical weekly patterns, the year was divided into months of similar heat demand and the average demands for each half hour in those months are shown in Figure 4-13. Figure 4-14 shows the average curves with their standard deviations for each half-hour period of the week in both the coldest three months (January, February, March) and summer (June, July, August). January, February and March registered Degree Day values at Bingley weather station that were respectively 18%, 20% and 50% higher than the 20 year average as seen in Table 4-2. These were the coldest months in the dataset year, but in other years the degree day numbers indicate that December is on average colder than March.

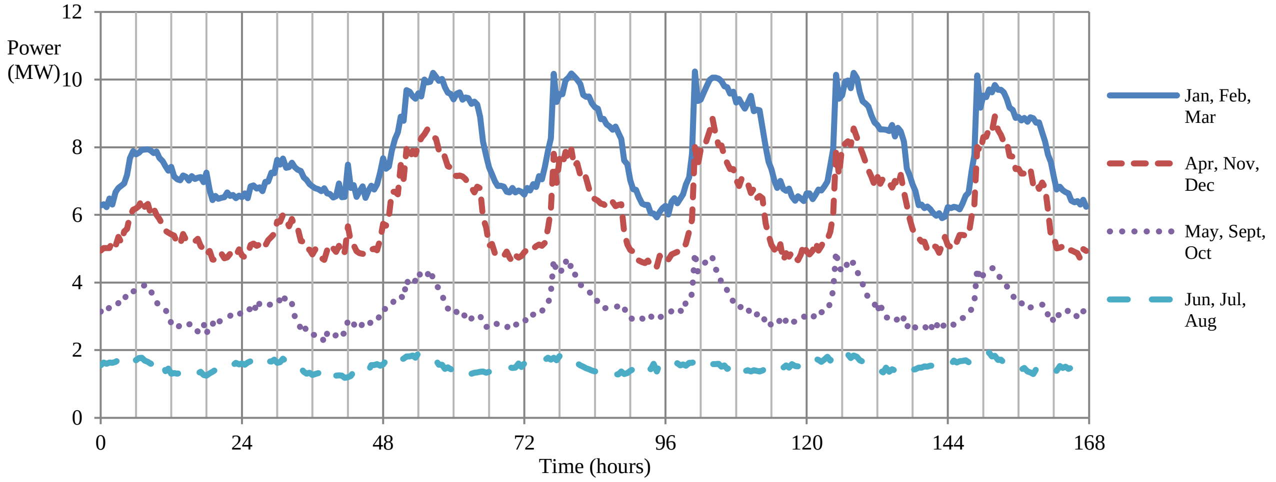

Figure 4-13: The mean heat demands for the University from July 2012 to June 2013, grouped into months.

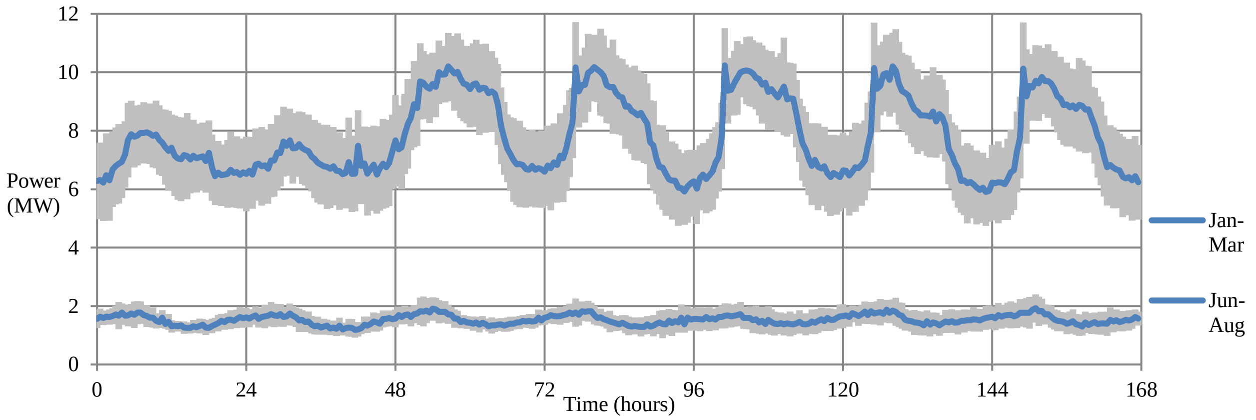

Figure 4-14: The winter and summer best fits for demand with error bars showing one standard deviation of heat demand for each half hour period during the week.

In Figure 4-13 it is shown that winter demand for the considered buildings often reaches a peak at around 6a.m. This suggests that some heating systems at the University are set on a timer in order to bring the indoor environment to temperature before staff arrive. This appears to be particularly true on a

Monday morning with an earlier rise in the demand in order to heat up buildings that have cooled down over the weekend.

Individual building heating characteristics

The heat demand variation of individual buildings has greater operational impact on a CHP unit if the number of buildings to be served by a new low-carbon heat source is low. For the University of Sheffield this will be a particularly important consideration if a new network for distributing heat is required.

After reviewing the data at an individual building level, one building was chosen as a focus due to high spikes in demand and seemingly quite erratic changes in demand. Figure 4-15 shows the demand trace over several weeks from a building during winter 2012/13. Also shown is the temperature record from the Centre for Environmental Data Analysis's MIDAS dataset (CEDA, 2015), as was used for analysis earlier.

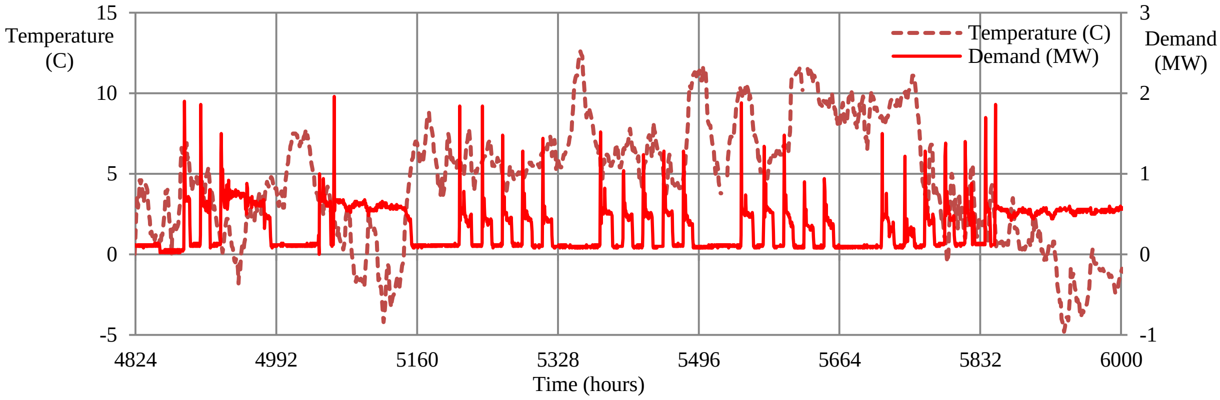

Figure 4-15: The heat demand and temperature from one building over seven weeks of winter.

When the outdoor temperatures are included, Figure 4-15 shows that the building heating controls vary the operational mode significantly depending on the outdoor temperature. When temperatures drop below a certain level, the heating switches to 24-hour heating mode, perhaps to protect parts of the building from frost. Above this temperature level, the weekday and weekend demands are markedly different and the transient effects of switching the heating on are significant. This spiking pattern may be a sign of 'night set-back' behaviour (Frederiksen and Werner, 2013) where the energy stored in the building heating system (including hot water tanks) are topped up when the heating is activated in the morning. Heat storage could help to manage some of the expected and unexpected demand variability. Better building-level control of heat storage capacity and heating systems could remove these sharp spikes in demand.

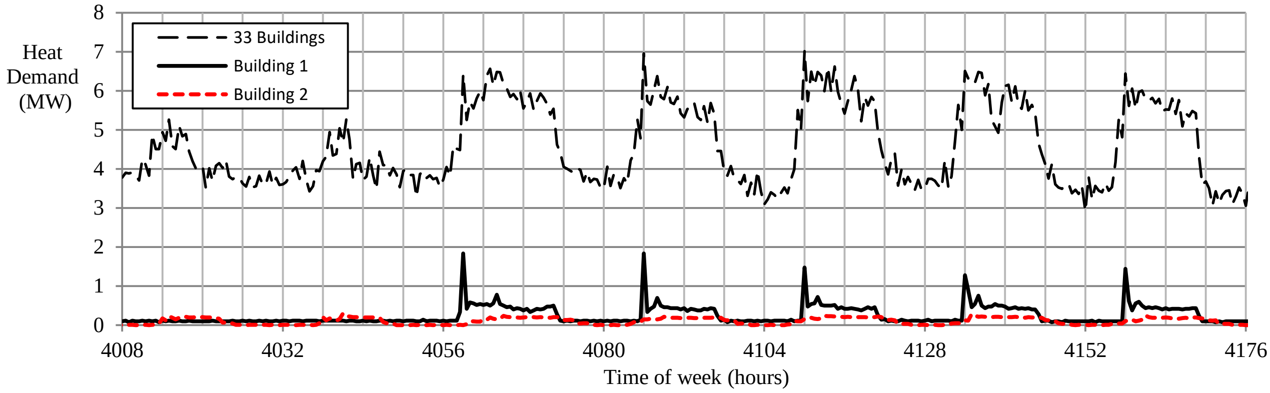

Figure 4-16: Half-hourly average heat demand for two buildings from Saturday 15th to Friday 21st December 2012.

Figure 4-16 shows one week with strong transient effects on the overall demand profile when switching on the heating system in the building featured in Figure 4-15. On Monday this switch-on occurs at around 3:30 am while on the other weekdays the switch on happens at around 6am.

The characteristic spike pattern seen in Figure 4-16 is present in many of the buildings but with less severity. After an initial high rate of heat consumption the heating demand falls to nearer a steady state where the rooms are at the desired temperatures and simply need maintaining at that state. Therefore the heat demand will be roughly equal to the rate of heat losses.

In other buildings the heat demand rises and falls more gradually. For comparison, the demand over the same period for another building is represented in Figure 4-17 with a smaller peak demands but a more consistent mode of operation.

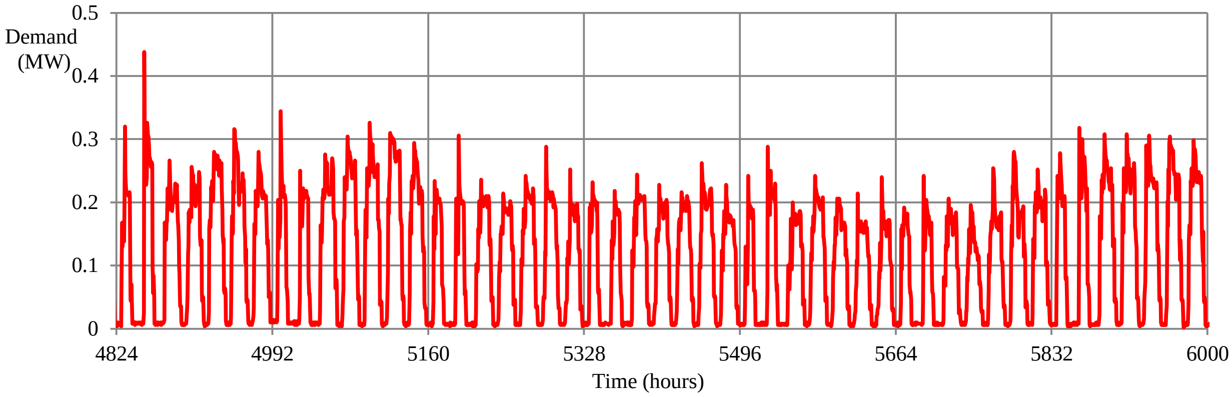

Figure 4-17: The heat demands each half hour over seven weeks of winter.

There are so many data points for the buildings on the campus that it was decided that a suitable approach was to find the ratio of peak demand versus the average demand over the whole day for each building on each day. Figure 4-18 looks at the spikes in demand from Building 1 from mid-November into December and it can be seen that some peaks are spread over two half-hour periods, thus reducing the probability of the spikes being a very-short-lived event that is not represented adequately by the half-hour readings.

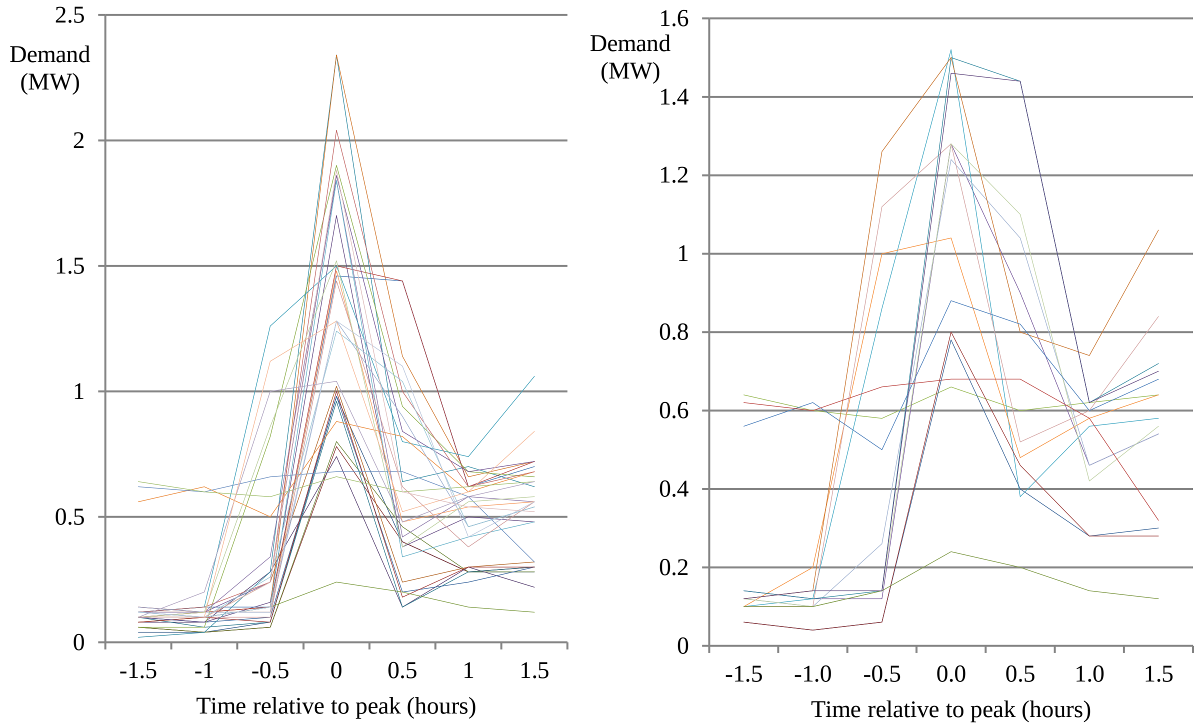

Figure 4-18: Detail of spikes in demand of Building 1, with a second diagram for the peaks that were less than double their nearest neighbour demand reading.

4.3.3 Spatial distribution of energy demand

In some circumstances heat storage can be used to alleviate bottlenecks in a heat network and where new infrastructure is being installed the spatial configuration of that demand can influence which loads are cost-effective to connect. For this reason, an aspect of spatial distribution of demand through the campus has been analysed.

Figure 4-19 shows a map of the main University campus with red circles indicating heat demands supplied by the DH system. The Goodwin Centre, at the western end of the campus, is the most difficult point of the city-wide heat network for the operators to maintain supply because of distance from the Energy Recovery Facility near the city centre as well as an uphill gradient from east to west. In Figure 4-19, the circle areas are proportional to the annual heat use per building.

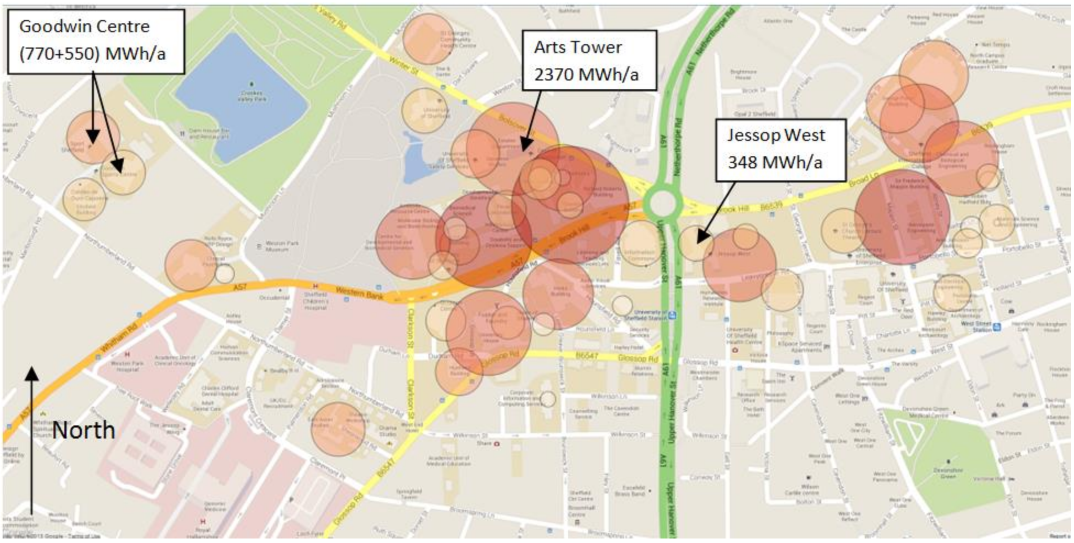

Figure 4-19: The building-level heat demands and their locations across campus.

In order to simplify the analysis, the buildings on this part of the network were divided into clusters as shown in Figure 4-20. The levels of heat demand for each numbered cluster are listed in Table 4-3, with by far the largest demands arising in Zone 6.

There are buildings in Figure 4-20 that do not belong to the University, notably the Weston Park Museum as the largest building in Zone 2, Weston Park Hospital buildings comprising Zone 3, and residential tower blocks comprising Zone 7. The Sheffield Children's hospital, just north of Zone 4 and west of Zone 5 in Figure 4-20 is also connecting a new wing to the city-wide heat network (SCNFT, 2015).

Zone 6 is the prime candidate for installing a CHP unit due to proximity to and resilience needs of large electricity and heat loads. Supply of heat may be possible through the existing heat network but may incur charges from the heat network operator. The alternative is to create a new direct link to nearby buildings in order to supply them with heat and reduce the amount that they draw from the DH system.

Figure 4-20: The zones used for network analysis.

Table 4-3: The heat demands of building clusters across the University campus.
Figures in brackets are estimates for the hospital in zone 3 and the council properties in Zone 7.
* indicates that Weston Park Museum's Consumption is also in this zone.

Zone	Annual Demand (MWh/year)	Average Demand (MW)	% of University heat demand
1	2290	0.26	5.6
2	771*	0.09	1.9
3	(3500)	0.40	
4	908	0.10	2.2
5	6228	0.71	15.3
6	18040	2.05	44.3
7	(1750)	0.20	
8	2079	0.24	5.1
9	4409	0.50	10.8
10	5979	0.68	14.7
TOTAL	40704 (+ 5250)	4.65	

4.3.4 Heat network bottlenecks

In heat networks, pipeline diameters are defined according to the expected levels of hot water flow required to supply the consumer needs downstream; for this reason the pipe diameters generally fall with distance from the main heat sources. Figure 4-21 shows some figures for pipeline internal diameters (in millimetres) as the city-wide heat network branch crosses the University campus towards the edge of the network. The branches running from the trunk up to individual buildings are small and typically made from DN80 pipes (Veolia Environmental Services, 2010).

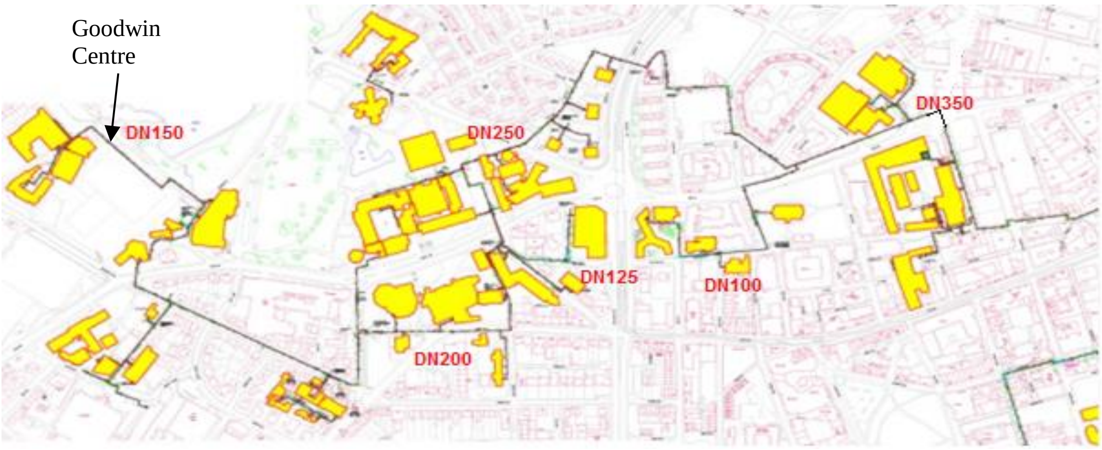

Figure 4-21: Heat network layout through the University, along with figures for local pipeline diameters in mm. Source: ARUP (2012)

Capacity limits on the pipelines could limit the feasible discharge rates of heat from a storage tank, particularly if the tank is near the periphery of the network where pipes are smaller. For example, the DN150 pipes serving the Goodwin Centre would allow a heat store there to serve the cluster of buildings in Zone 1 (average demand in December of roughly 0.5 MW) as well as sending around 5 MW of heat back down the network as seen in Equations 4.47 to 4.50.

$$P_{th} = \rho . \frac{dV}{dt} . c . \Delta T \tag{4.47}$$

$$\frac{dV}{dt} = \pi \frac{d^2}{4} v \tag{4.48}$$

$$P_{th} = 850 \times \pi \times \frac{0.150^2}{4} \times 3 \times 4.2 \times 30 \tag{4.49}$$

$$P_{th} = 5680 \text{ kW} \tag{4.50}$$

Two sites amongst the University campus were judged as having potential for heat storage by Veolia (ARUP, 2012): near the Octagon Centre and near the Goodwin Centre.

4.3.5 Electrical demand and infrastructure

The campus buildings overall use around 40,000 MWh of electricity per year (ARUP, 2012), approximately the same as their DH consumption. The electrical infrastructure through the University of Sheffield's campus will influence how the CHP unit can operate. The most valuable production of electricity is that which displaces the import of electricity and in particular that during the day periods when prices are higher.

The University of Sheffield Energy Strategy identified the metering zones for electricity across the campus and will give a good indication of the electrical loads that can be met by on-site CHP generation. The zones are shown in Figure 4-22 and this central electrical circuit approximately corresponds to Zones 5 and 6 from section 4.3.3.

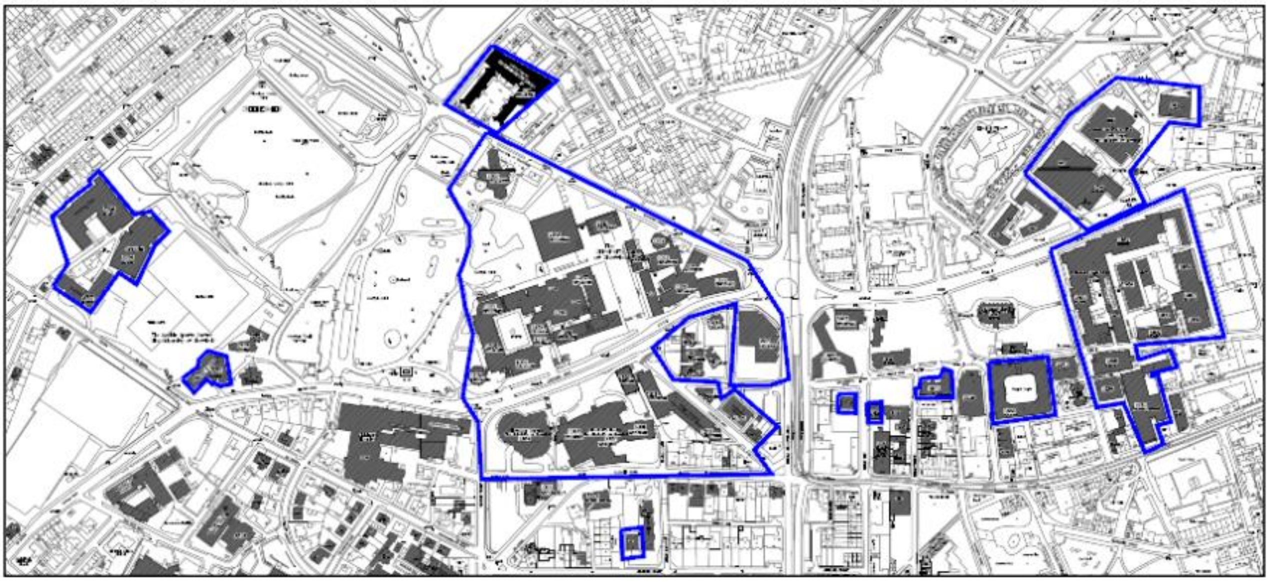

Figure 4-22: Electrical metering zones across the University campus.
Source: ARUP (2012).

The buildings in the main electrical metering zone are considered as possible electrical loads for the CHP unit. Approximate electrical demands for buildings featured in the University's energy strategy (ARUP, 2012) according to zone are shown in Table 4-4. The available electrical load for the main electrical ring (Zones 5 and 6) comes to 26,320 MWh per year.

Table 4-4: Electrical demand according to zone.

Zone	Estimated Annual Electricity Demand (MWh)
1	430
2	860
4	780
5	8230
6	18090
8	1350
9	4500
10	6720

4.4 Modelling CHP and heat storage

4.4.1 Introduction

Given the heat demands of the University buildings as explored in Sections 4.2 and 4.3, it is not a simple matter to evaluate the costs and benefits of implementing heat storage. A simulation of CHP operation with heat storage was developed with Visual Basic automation in Microsoft Excel.

The principles of operation of CHP units were explored in Section 3.1.4. Natural gas is the assumed fuel in this instance in accordance with the proposed energy strategy and in common with CHP schemes at other univeresities (see Table 2-9). This CHP unit would reduce the emissions related to electricity significantly under current grid conditions but the impact on reduction of emissions from heat would be small due to displacement of the heat network's relatively low-carbon heat supply.

A new CHP is most efficient when heat rejection to atmosphere is limited, however there is a trade-off since a larger CHP engine could meet a greater proportion of heat and power demands. CHP engines can be modulated to produce lower outputs although the electrical efficiency is reduced as a consequence. If radiators are installed with the CHP, excess heat can be rejected from radiators if there is insufficient access to heat load at some times of year.

Heat losses from the heat network will result in a continuous but small loss of energy. The quantification of this heat loss was explored in Section 3.2.3 and the specific approach applied in this chapter is described in Section 4.5.2. These losses increase the heat demand that needs to be met and the carbon factor of delivered heat accounts for this loss. Additional heat distribution pipework at the University will increase the level of heat losses.

4.4.2 Operation pattern modelled

Typically, CHP engines are run in one of two modes: electrical-load follow or heat-load follow. Electrical load follow mode typically allows for maximised use of CHP-generated electricity on the site and no export of power. When heat demand is low compared to the rate of heat recovery from the engine but production of electricity is still cost-effective, there may be significant rejection of heat to the atmosphere. There are also limits on the range of modulation for CHP engine's electrical outputs with units typically able to run at no less than 50% electrical output. Heat load follow is the other operational mode where the engine is sized for a good fit of the site's heat demand but this may mean that a large fraction of electricity still needs to be imported from the grid. Lower heat rejection in the summer months will mean better environmental performance. The complexity of these considerations mean that different approaches will be required to best suit the needs of different sites.

Where storage is implemented, the CHP engines are modelled to run for as many half-hours as possible without exceeding an output equal to the total heat demand of the day so that the store cannot accumulate excess heat over multiple days. These running periods were successively scheduled in Microsoft Excel according to a priority rating for each half hour defined with respect to avoid the highest electricity charges as well as to allow for continuous running as far as possible. The overall balance between supply and demand led to either charge or discharge of the heat store through time. The heat store enhances run hours in the heat load follow scenarios and reduces heat rejection in the electrical load follow scenarios.

There is no explicit electricity price signal modelled in this chapter, but the greater use of CHP during the peak times occurs as a result of a defined priority sequence. Those periods around the evening peak times were given the highest priority while the periods overnight were given the lowest priority. Where two engines were in operation the second engine was only activated once the first was running throughout the day.

The remaining heat required beyond that produced from the CHP units on site is made up using heat from the city-wide district heating network. Any stored heat in the tank at the end of the day was carried over to the following day. Greater detail of the algorithm including the priority sequence can be found in Appendix 10.3.

4.4.3 Operating costs

In 2011, the gas price for the University was around £33/MWh (ARUP, 2012) but gas prices have fallen significantly in recent years. The University pays a premium for a "Green Electricity" tariff but additional cost is offset by exemption from the Climate Change Levy (CCL), although there is no carbon emission benefit applicable under the Carbon Reduction Commitment (CRC) scheme (*ibid.*). The economic impact of various incentives are explained in Sections 3.4.4 and 3.4.5.

Top up heat from the city-wide DH system can be used to meet part of the heat load for buildings and this is currently paid for at a flat unit rate (University of Sheffield, 2013d). There is a cost to the University for heat from DH under the CRC proportional to the carbon factor of heat produced (ARUP, 2012), this economic benefit is not modelled since the CRC is set to be abolished in 2019 (HM Treasury, 2016). 'Use of system' charges may apply if heat is to be transmitted using the existing DH system.

The electricity value will depend on whether that electricity is displacing the use of day or night rate electricity imported from the grid. The output of the on-site CHP will also reduce the charges for distribution use of system costs and the transmission network use of system costs typically calculated through reducing the demand during triad periods as explored in Section 3.4.2. Time dependent pricing of electricity was not explicitly modelled but the priority sequence ensures that the CHP is most likely to run when the cost of electricity is greatest.

Overall operating expenditure assumptions are listed in Table 4-5. In each modelled scenario an estimate of the overall operation costs is derived in order to demonstrate any economic advantage delivered by the CHP unit.

Table 4-5: Operating expenditure assumptions.

Economic Assumptions	Value	Units	Comments
Natural gas cost	30	£/MWh	2011 gas cost of £33/MWh (ARUP, 2012) with downward adjustment reflecting falling market prices.
Electricity value	100	£/MWh	Average non-domestic energy prices in Q3 2016 were at around £95/MWh (DECC, 2012f) with an additional £5/MWh assumed for value of "green electricity".
Heat value	35	£/MWh	University of Sheffield spent £1,464,600 on District Heating in 2013-14 (University of Sheffield, 2015b), assuming 40,000 MWh of consumption this is £36.6/MWh.
CHP O&M	6	£/MWh	£67.52 per kW per year according to Element Energy (2015)

4.4.4 Capital costs

Installing a CHP and necessary boilers has an associated capital cost as well as the necessary electrical and thermal infrastructure works required. Some buildings may require dual heat exchangers to allow acceptance of heat from both the onsite CHP and the city-wide heat network. The University expects the project overall to have a capital expenditure of £17 million (University of Sheffield, 2015c).

A pressurised hot water tank would be required if the heat is to be stored at the temperature and pressure used on the existing heat network. Store costs were discussed in Section 3.4.9 with the relevant cost assumptions given in Table 4-6.

Table 4-6: Capital cost assumptions.

Capital cost assumptions		Notes
Heat storage fixed cost	£25,000	Estimated costs that are independent of store scale
Heat storage installed cost (variable)	£1000/m^3	Based on cost data described in Section 3.4.9.

4.4.5 Environmental analysis

Gas carbon factors published by government and marginal emission factors for the electricity grid have been used in order to assess overall carbon emissions impact, as noted in Section 3.6. The heat supplied from DH also carries a carbon intensity factor from the combustion of fossil fuels and municipal solid waste in this instance to generate the heat. The emissions factor for DH supply was detailed in Table 4-1.

Sheffield City Council's proposed 'Clean Air Zones' may limit the options for the University to implement self-generation (ARUP, 2012). There are very tall residential and University buildings near the proposed energy centre site and therefore achieving adequate flue gas dispersion may be difficult. These are issues that will present at the planning stage, and it is assumed that the proposed configurations of the modelled interventions are able to get planning permission.

4.5 Scenarios and case study results

The University of Sheffield is an unusual case study compared to the UK universities described in Table 2-9 since there is an existing connection to a city-wide DH scheme. The charges and infrastructure requirements of top-up heat from the DH network are quite different to those for installing and operating gas boilers for top-up with implications for resilience, too. If access is enabled, excess heat production from the University's CHP could be put to use by distribution to other sites through the city-wide network; speculating on the possible commercial arrangements for this is beyond the scope of this work.

4.5.1 Outline heat load scenarios

The heat load scenarios considered were:

- 1. Sinking all excess heat into the city-wide DH network;
- 2. Using the city-wide network to reach all the University's DH-connected buildings; and
- 3. Serving close by University buildings through a new heat network.

Figure 4-23 illustrates the physical configurations of the network, for which the exiting situation is shown in diagram (a), scenarios 1 and 2 would equate to diagram (b) and scenario 3 would require a new parallel network as in diagram (c).

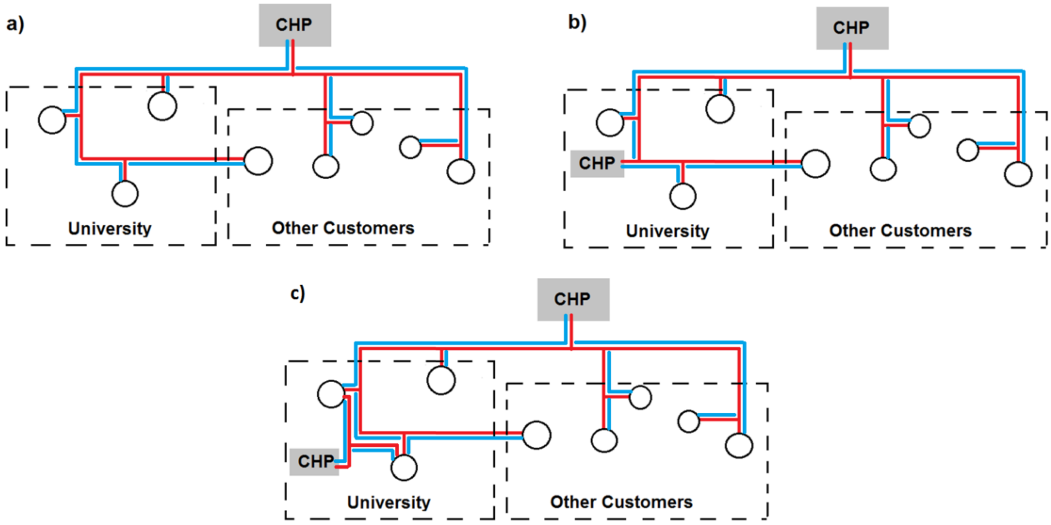

Figure 4-23: A schematic of the University in relation to the city-wide heat network to illustrate the different supply scenarios.

Heat demand data from the University was used to construct a demand-duration curve, differing from the load-duration curves discussed in Section 2.3.1 by the exclusion of losses. Figure 4-24 shows the demand-duration curve for the University for the 8760 hours in a year derived from the meter readings data set and scaling this to cover the whole campus since the complete record only covers 66% of the campus heat demand. The detail of the peak in demand is shown in Figure 4-25.

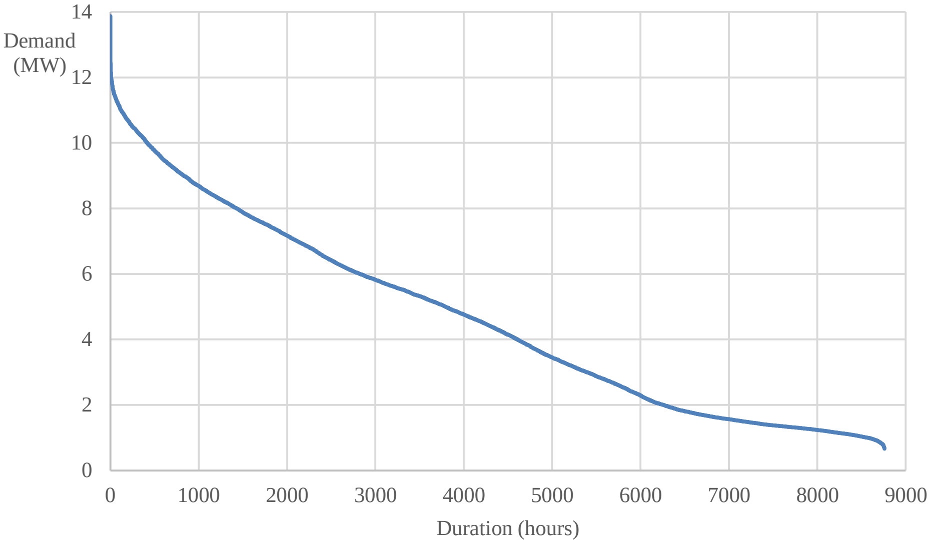

Figure 4-24: Demand-duration curves for the heat demand over a year for the whole campus. The right hand diagram shows the detail of the 20 half-hours with the highest demand levels.

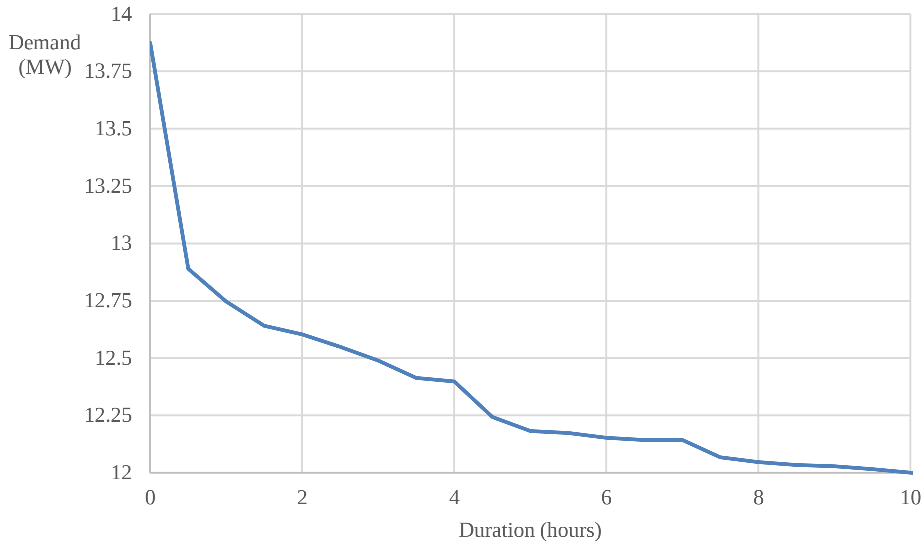

Figure 4-25: Demand duration curve showing greater detail on the highest heat demand periods.

This demand shown in Figure 4-24 and Figure 4-25 is based on heat meter readings, and in addition to this there will be heat losses from the heat network before the heat reaches the customer's meter which have not been accounted for yet. The heat losses constitute the difference between the demands seen at the meters and the load to be seen by the heat supplier.

To quantify these losses, reference is made to the city-wide network load shown in Figure 4-2 which includes heat losses; the load was seen to drop to a minimum of approximately 4 MW in summer. The network-wide heat losses are assumed to be consistently 2.5 MW and, considering the network map of Figure 4-1,approximately a fifth of the pipe length of heat network lies in the University's campus and therefore the heat losses through the campus are estimated as an additional 500 kW in addition to the heat demand seen above.

A loss of 2.5MW over the entire network would correspond to 21,900 MWh per year or approximately 20% of the heat load. While this is more than the 10% losses best practice in the new Heat Networks Code of Practice (CIBSE and ADE, 2015), it is a reasonable number given the age of the network and the use of Series 1 pipes in its construction (RK District Heating, 2016) which is lower than the insulation level seen in some modern networks (Series 2 or Series 3).

For scenario 1 where excess heat can be rejected to the city-wide network, the load can be approximated as the demand curve of Figure 4-24 multiplied by a factor such that the heat demand plus 2.5 MW of year-round heat losses add up to 120,000 MWh per year. In reality, the shape of the load duration curve will be slightly different for the city-centre network due to the different overall nature of heat loads present including residential, office, health and commercial buildings.

For scenario 2 concerning distribution of heat to University buildings only, the network branch heat loss is estimated at 500 kW and heat demand is that of the all University buildings. The University's energy centre is expected to meet both parts of this load, importing heat from the city-wide network as top-up when necessary. The annual load to be met becomes just under 45,000 MWh under these assumptions.

For scenario 3, a new heat network is installed to nearby buildings, having a year-round heat loss of 300 kW and has access to half of the University's heat demand (approximately 20,700 MWh per year). The heat demands in each of the scenarios are calculated as in the Equations 4.51 to 4.53.

$$Q_1(t) = Q_{UoS}(t) \times (\mathrm{AD_{CW}} - 8760 \times \mathrm{HL_{CW}}) / \sum_t Q_{UoS}(t).\Delta t + \mathrm{HL_{CW}} \tag{4.51}$$

$$Q_2(t) = Q_{UoS}(t) + \mathrm{HL_{UB}} \tag{4.52}$$

$$Q_3(t) = Q_{UoS}(t) \times \mathrm{AD_{UN}} / \sum_t Q_{UoS}(t).\Delta t + \mathrm{HL_{UN}} \tag{4.53}$$

Where $Q_i(t)$ is the half-hourly average demand in scenario i, Q_{UoS} is the University's metered demand (excluding external pipe losses), $AD_{CW/UN}$ is the annual heat demand of the city wide network /University network, $HL_{CW/UB/UN}$ is the heat loss for the city-wide network/ University branch of the city-wide network/ University's new local heat network for the CHP installation. The load duration curves for these three scenarios are shown in Figure 4-26.

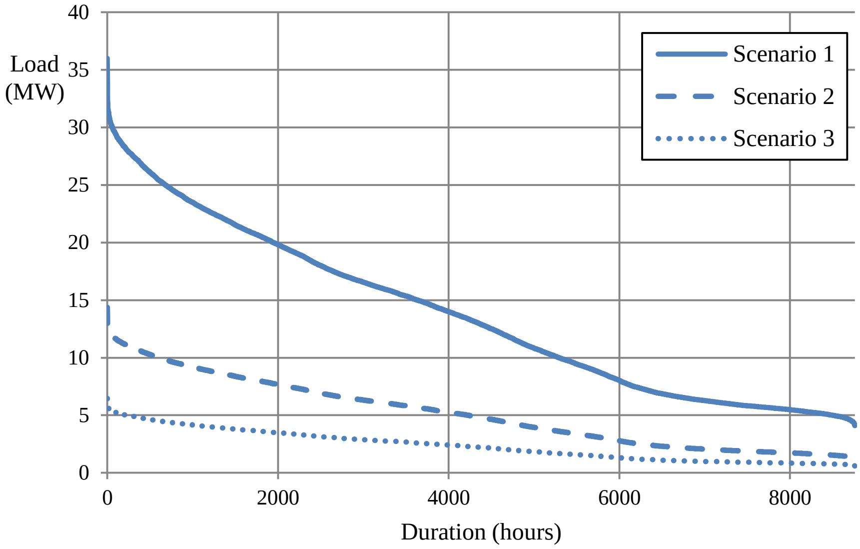

Figure 4-26: The modelled loads for the three scenarios for meeting the University's heat demands.

4.5.2 CHP Heat Load Follow, no thermal storage

In line with the University's expectations of a 2 MW_e/2MW_{th} gas reciprocating engine CHP option (University of Sheffield, 2015), the above three scenarios for possible heat loads were used to simulate the CHP's operation. Assuming 24/7 operation as heat-load follow without interruption except for 5% of the year as unavailable time gave energy output values as in Table 4-7. The CHP is turned off when the heat demand falls below 50% output which constrains the output scenarios 2 and 3.

Table 4-7: Thermal energy produced from a single 2MW CHP under the three scenarios without heat storage.

Scenario	Thermal Energy Produced (MWh)	Percentage of potential production(%)
1	16,644	95.0
2	16,221	92.6
3	12,869	73.5

It can be seen from Table 4-7 that if the heat distribution is limited to the local buildings (Scenario 3) the CHP's output is constrained by approximately a fifth compared to Scenario 1. Since the electricity production from the CHP is greater than the electricity demand of loads that are likely to be connected (those in Zones 5 and 6 of Figure 4-20 totalling 16,320 MWh per year), operation in heat load follow means there will be export of electricity. Mismatches between electrical and thermal load timing mean that there is likely to be significant export of electricity which would achieve lower value (if any value at all) compared to displacement of electrical import. Accordingly an electrical load follow scenario has also been developed.

4.5.3 CHP Electrical Load Follow, no thermal storage

Assuming a largely stable electrical demand formed from demands in Zone 5 and 6 shown in Figure 4-20 of 26,320 MWh per year, a profile of the electrical demand was constructed since electrical data was not available for this study. After a review of the available electrical load profiles in the literature, a non-domestic electricity demand profile used by ELEXON to settle electricity trading agreements (ELEXON, 2013). This profile is a weekday profile and was reduced by 25% to model a Saturday, and a further 25% to model a Sunday. This weekly demand profile was assumed to persist evenly throughout the year and was multiplied by a factor such that the annula demand equalled 26,320 MWh as required. The resulting profile is shown in Figure 4-27.

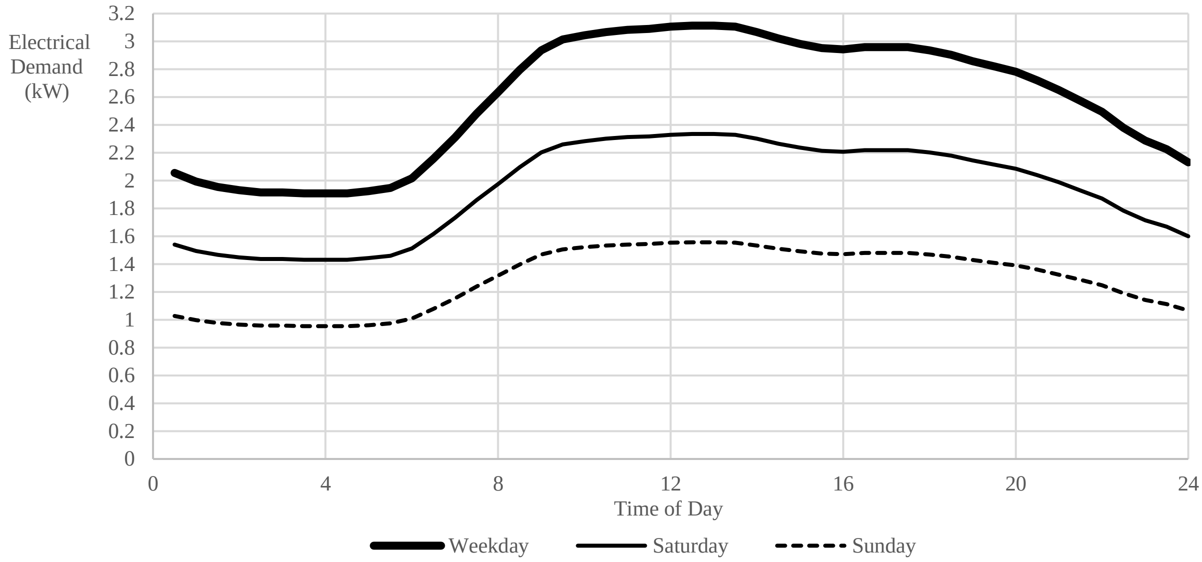

Figure 4-27: Constructed Non-Domestic Electricity Demand Profiles for Electrical Load Follow model.

It is immediately clear from constructing these profiles that the electrical demand seen on the central part of the campus may be much better suited to a single 2MW CHP compared to two of these. Following the electrical load constrains the CHP output significantly compared to heat load follow scenarios. There may be difficulty in securing revenue for electricity export and therefore this constraint is a sensible assumption for economically viable schemes at the University.

When running in electrical load follow, the heat utilisation becomes a measure of the efficiency of differerent running patterns and depends how much heat demand can be served as discussed in Section 4.5.1. Results for these distinct heat load scenarios without storage are given in Table 4-8.

Table 4-8: Electrical Load Follow scenario results.

	Electricity generated (MWh)	Heat Utilised Scenario 1 (MWh)	% Heat Utilisation	Heat Utilised Scenario 2 (MWh)	% Heat Utilisation	Heat Utilised Scenario 3 (MWh)	% Heat Utilisation
1x4MW	19,398	19,398	100%	17,316	89.3%	14,149	72.9%
1x3MW	21,678	21,678	100%	19,797	91.3%	16,458	75.9%
2x2MW	22,268	22,268	100%	20,163	90.5%	16,639	74.7%
1x2MW	16,541	16,541	100%	16,129	97.5%	13,857	83.8%

As can be seen from Table 4-8, in general the smaller CHP engines generate much more electricity; this is due to the lower value of the 50% turn down output giving a greater ability to meet electrical demand during low electrical demand periods.

Heat storage has most potential when electrical load following leads to a mismatch of heat and power demands and therefore low heat utilisation. The power load is fixed across the three scenarios as the electrical load is likely to be fixed to zones 5 and 6 as above. Significant heat rejection is predominantly the case in scenario 3 where the heat demand seen by the CHP is the lowest and in the scenarios with only the large CHP unit. Since the presence of a 2MW CHP means a better match to expected load variations, this is the scenario modelled in most detail.

4.5.4 Heat Load Follow with Energy Storage

The model tests the configuration with and without heat storage for the circumstance where the heat network can be used to supply all the University buildings on the heat network but no others (Scenario 2). A description of the running patterns modelled was given in Section 4.4.2.

Figure 4-28 shows how the stored energy varies under heat load follow scenarios with 4 MW CHP and 2 x 2 MW CHPs. In summer the store fills up with energy while the CHP is running and the store discharges when the CHP is off (usually during the night time). In the coldest parts of winter, the CHP runs consistently at full output and the store is rarely required for the University's own CHP unit.

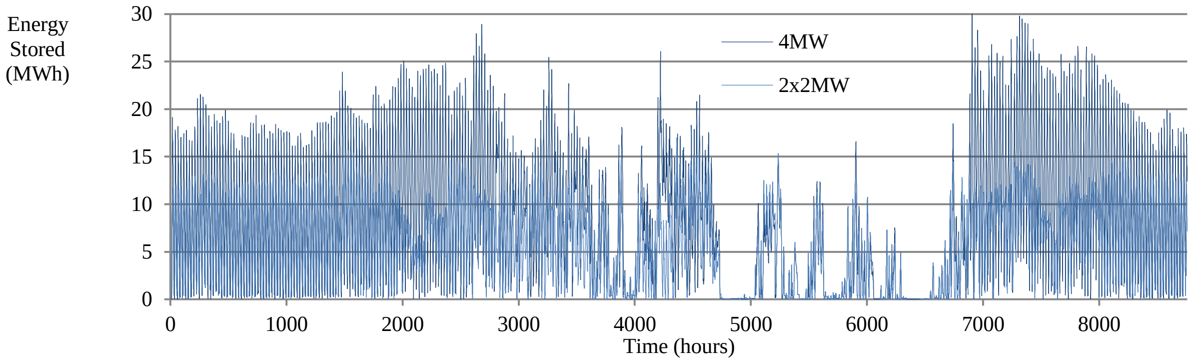

Figure 4-28: Simulated use of storage where heat production serves University buildings only.

The year-average load factors according to each half hour of the day were as shown in Figure 4-29 where no heat storage is present. When heat storage is introduced and the CHP unit production is allocated toward peak times of day but limited to produce at most the amount of heat required to meet the heat demand that day, but store the energy when required, the resulting diagram is given in Figure 4-30.

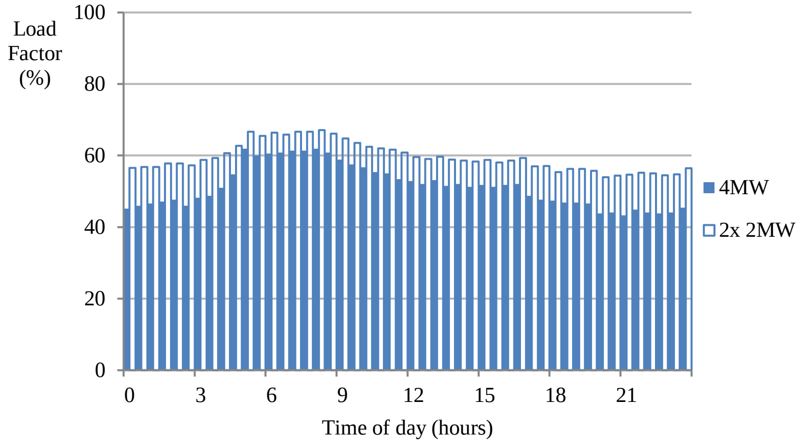

Figure 4-29: Year-average load factor for the CHP units according to time of day without heat storage.

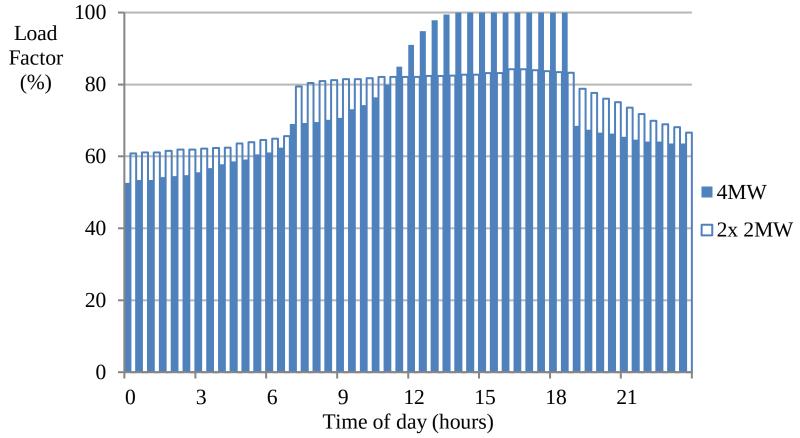

Figure 4-30: Year-average load-factor for the CHP units according to time of day with heat storage.

In Figure 4-31 and Figure 4-32, the energy production according to time day and time of year are illustrated. Figure 4-31 shows the scenarios without storage for one 4MW unit and two 2MW units. The energy contributions are significantly higher in the cooler six months due to the higher levels of heat demand, in summer there is very little running of the engine if any unless storage is used.

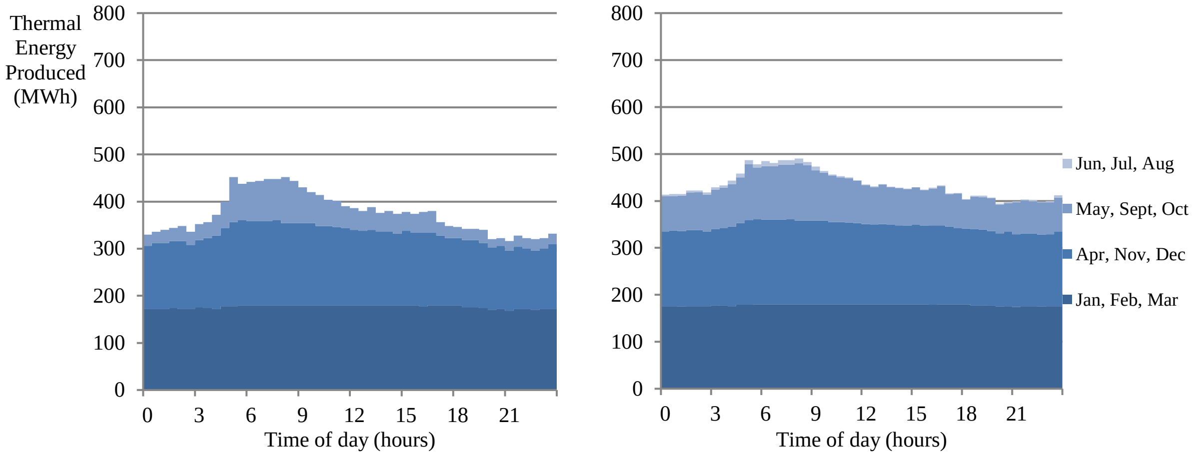

Figure 4-31: Energy production according to time of day in scenarios without heat storage.

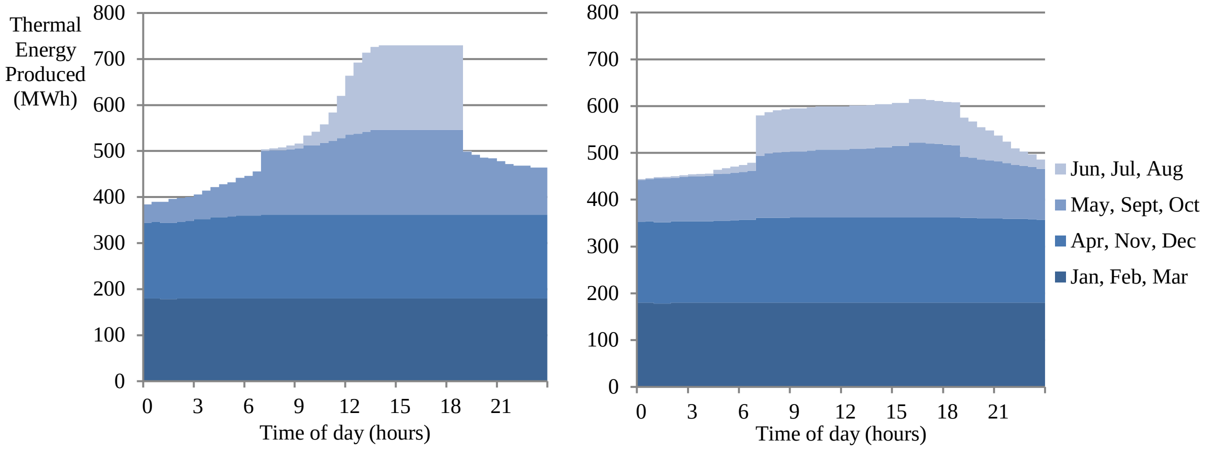

Figure 4-32: Energy production according to time of day in scenarios with heat storage.

Figure 4-32 demonstrates that using heat storage with the CHP units really enables a much bigger contribution from the engines in the warmer months.

4.5.5 Electrical load follow with Energy Storage

For electrical load follow scenarios, the timing of CHP running depends on the electrical profile and does not change depending on the introduction of heat storage. These scenarios have been modelled with the heat load of Scenario 3 as described in Section 4.5.1. There are benefits from introducing storage in terms of lower rejection of heat to atmosphere and there is also potential for providing heat storage service for the wider DH network. The store simply charges when there is heat that would otherwise be rejected, and discharges when top up heat from district heating would be required. The numerical results of these simulations are given in Table 4-9 using thermal store capacities up to 100 m^3. Carbon emission savings were calculated using emission factors as described in Section 3.6. Cost assumptions are as described in Sections 4.4.3 and 4.4.4.

Table 4-9: Results from the modelled electrical load follow scenarios with a single 2MW CHP able to modulate down to 50% output and meeting the heat demand of Scenario 2.

Storage capacity	No storage	0.75 MWh	1.50 MWh	2.25 MWh	3.00 MWh
Store volume (m^3)	-	25	50	75	100
Annual CHP heat output (MWh)	16,541	16,541	16,541	16,541	16,541
Annual CHP heat utilised (MWh)	16,129	16,213	16,238	16,255	16,267
Additional heat utilisation (MWh)	-	83	109	126	138
Annual CO_2 saving (tonnes):					
a) DH counterfactual and top-up	1,831	1,842	1,846	1,848	1,850
b)gas boiler counterfactual and top-up	3,355	3,375	3,381	3,385	3,387
Additional Capital Cost (£’000)	-	50	75	100	125
Annual DH Heat Cost Saving (£)	-	2,916	3,818	4,403	4,816
Simple Payback Time (years)	-	17.1	19.6	22.7	26.0

Table 4-10: Results from the modelled electrical load follow scenarios with a single 2MW CHP able to modulate down to 50% output and meeting the heat demand of Scenario 3.

Storage capacity	No storage	0.75 MWh	1.50 MWh	2.25 MWh	3.00 MWh
Store volume (m^3)	-	25	50	75	100
Annual CHP heat output (MWh)	16,541	16,541	16,541	16,541	16,541
Annual CHP heat utilised (MWh)	13,857	13,910	13,942	13,964	13,980
Additional heat utilisation (MWh)	-	54	86	107	123
Annual CO_2 saving (tonnes):					
a) DH counterfactual and top-up	1,520	1,527	1,531	1,534	1,536
b) gas boiler counterfactual and top-up	2,829	2,842	2,849	2,854	2,858
Additional Capital Cost (£’000)	-	50	75	100	125
Annual DH Heat Cost Saving (£)	-	1,879	3,000	3,760	4,307
Simple Payback Time (years)	-	26.6	25.0	26.6	29.0

The analysis shows that the installation of a hot water store would have a simple payback period of between 17 and 25 years depending upon the heat demand that is served by the CHP. This payback is unlikely to justify the capital investment involved in including heat storage.

4.6 Discussion

4.6.1 Operational modes

Two operational strategies have been considered for a CHP installation at the University: heat load follow and electrical load follow. Since the electrical load available is significantly less than the heat load that can be accessed via the heat network, these two scenarios have markedly different results. The heat load follow scenarios favour a large CHP engine in order to meet a significant fraction of the heat load. The carbon savings for heat load follow would be much more than seen at other university CHP schemes, provided carbon credits for export were realised, however the economics of heat load follow are in question. A low expectation of tariffs available for export means the high-export, heat load follow scenario is unlikely to be economically viable. The elerctrical load follow scenario is much more likely to materialise but would meet a lower fraction of the University's demands. The carbon savings from this scenario are much less but these results are much more consistent with other university CHP systems seen in Chapter 2, allowing for these conclusions to be validated.

The heat store operation has only a small effect on a CHP that is operating in electrical load follow. There is some improvement in heat utilisation as excess heat at one time can be captured and used at a later time. This does not however provide a decent return on investment in itself. There may however be additional revenue possibility in this case study because of the link to the city-wide heat network. Additional revenue for the store may be realised by allowing the heat demand from the city-wide network to be time-shifted; this would mean that the steam turbine CHP could produce more electricity at peak times. The benefit of a heat store for the city-wide heat network is explored in Chapter 6.

4.6.2 Demand level

Three scenarios were used in the chapter to illustrate differing levels of heat demand to be met by the CHP unit. The outcome of discussion by the University and the city-wide DH operator on whether feeding excess heat into the existing network will be important and it is currently unclear the position of the stakeholders on this which is why it was necessary to consider different scenarios.

Summer demand could be increased by adding an absorption chiller to use heat for cooling which could then be distributed to nearby buildings via a new cooling network. However, an insufficient number of customers for cooling were identified and therefore this option was not explored in the modelling. The potential for feeding excess heat into the network is a much more apparent possibility and should be explored first.

4.7 Summary and Conclusions

The work in this chapter has addressed a lack of heat demand data for buildings on heat networks by providing data and analysis of demand patterns as well as investigation of diversity factors which are crucial for effective heat network design. This work addresses the lack of information by studying the demands of buildings in the University of Sheffield which are connected to a city-wide heat network. This study comes at an important time as the University is considering connecting a new CHP unit to self-supply heat and electricity, and the scope for heat storage to significantly improve the environmental and economic outcomes of operation of CHP units has been demonstrated.

A diversity factor of 0.454 was found across 33 buildings of the University of Sheffield estate, meaning that the necessary boiler plant could be of a significantly lower capacity for buildings connected via a network and that use of thermal storage deployed at a multi-building level would need to meet a lower peak demand.

The demand data provided clear evidence of the influence of external temperatures, time of day and day of week on the heat demands per building. Some of the buildings have been shown to draw a large amount of heat over a short period in the mornings after a near switch-off overnight and this could place a noticeable strain upon the heat supply systems. However, other buildings do not draw sharp spikes and have a heat demand that varies more steadily. It will be good practice for managing the heat supply system to make sure that these spikes of demand do not coincide where possible, and changes to building heating controls may be able to eliminate these spikes.

The benefits of feeding excess heat from a new CHP unit into the wider heat network, rather than just feeding nearby buildings, were demonstrated. The use of heat storage alongside the new CHP unit would allow a greater thermal efficiency by rejecting less heat. The additional carbon savings would be in the region of 16 to 19 tonnes of carbon dioxide per year which is small due to the use of low carbon heat for top-up; with gas boilers used for back up the benefit would be 29 to 32 tonnes. A thermal store installation would achieve an economic payback of 17-25 years, which is not particularly attractive for an investor, but the revenues and carbon savings could be enhanced significantly by time-shifitng of heat demand on the city-wide network and this will be explored in Chapter 6.

5 HEAT STORAGE FOR INDUSTRIAL HEAT RECOVERY

5.1 Introduction

This chapter investigates the potential for heat storage and district heating (DH) to achieve industrial heat recovery in Sheffield. A large new extension to the city's DH network increases the opportunity for capturing waste heat from industrial areas. This research work has developed a new computational model to determine the benefits of incorporating waste heat recovery and heat storage in the DH system, including the impacts upon the other heat sources connected to the network.

A literature review of industrial heat recovery was integrated with the thesis literature review and discussions with industry were undertaken to further understand the industrial processes and the production of waste heat. Mechanisms to capture and distribute the waste heat were also reviewed in order to develop a suitable approach to heat recovery. This case study considers arc furnace steelworks only, but many of the barriers to heat recovery are similar for other types of industry.

An original DH model was developed to demonstrate incorporation of captured waste heat into the network and also to show the potential role for heat storage in achieving this. The model was developed in the C++ programming language, making it possible to maximise the freedom of choice for operational parameters. In particular, the consequences for the other heat sources on the network were significant such as the addition of industrial heat to the network meaning the CHP unit produces less heat and more electricity for the grid. The role for heat storage in capturing industry heat also had wider benefits for the network by reducing costly gas boiler use and allowing the CHP unit to generate more electricity at times of high demand.

5.2 Background and Literature Review

5.2.1 Waste heat transmission through the Sheffield DH network

Since heat networks are capital-intensive, transmission of large volumes of energy over a minimal distance is crucial for viability. Some industrial customers could benefit from pipes delivering steam at high temperatures, rather than DH supplying at temperatures suitable only for space heating and hot water preparation. If there is a cooling demand, absorption chillers can generate cooling from heat.

There are technical design issues to resolve when planning networks, the choice of pipeline diameter for network extension is important since a smaller pipe may reduce cost but also limits the heat-carrying capacity. The peak heating power that the pipes must carry determines the diameter and the availability of heat storage will affect design considerations. Heat stores can also be distributed around the network to deliver a flexible and design.

Sheffield has a long experience of DH technology compared with other UK cities. The city centre network is shown in Figure 5-1 along with the new network which will deliver heat from a renewable biomass CHP plant commissioned in 2014 and shown in Figure 5-2.

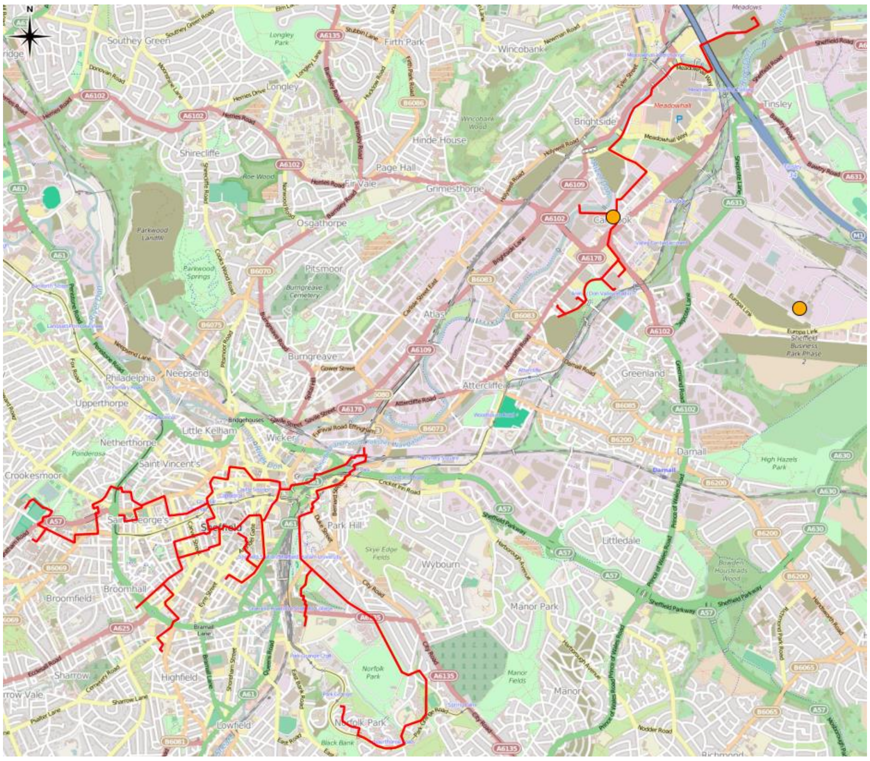

Figure 5-1: Sheffield's city-centre heat network (lower left), the new Lower Don Valley heat network (upper right), and Electric Arc Furnace locations (orange dots).
Note: Plot created with QGIS software (QGIS, 2015). Source: Map data from OpenStreetMap (OpenStreetMap, 2015).

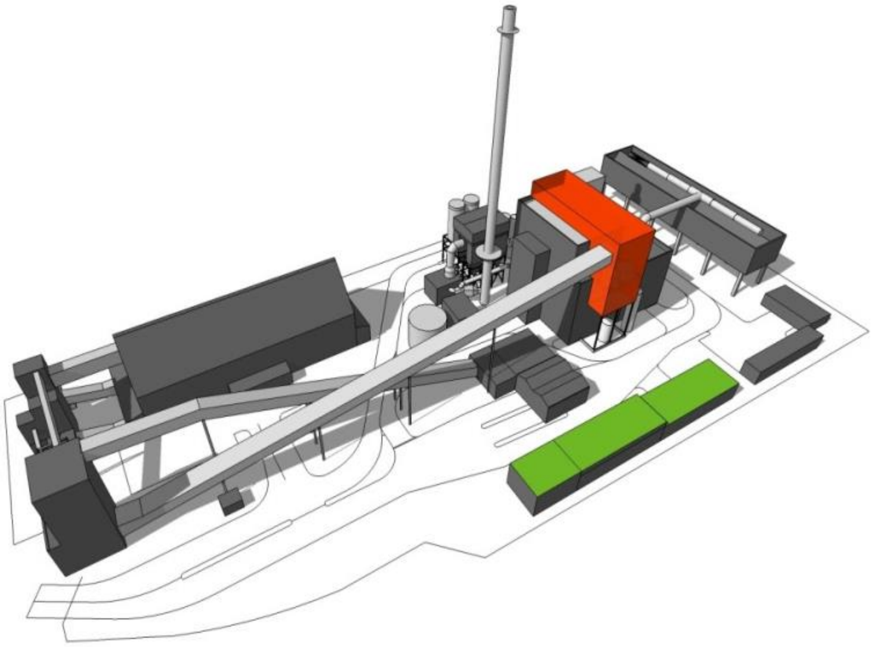

Figure 5-2: Blackburn Meadows Biomass CHP Power Station.
Source: TGM Kanis (2012).

This expanded network passes through parts of the city with greater industrial activity thus creating potential for capturing waste heat. Ten such industry sites have been estimated to have 1MW of waste heat potential each (Finney et al., 2012). The UK has four active steelmaking electric arc furnace (EAF) sites, two of which are in Sheffield (marked with orange dots in Figure 5-1), one in the neighbouring town of Rotherham, and the other in Cardiff (DECC, 2013n).

In this case study the steelworks considered is adjacent to the main branch of the heat network and therefore the mapping of heat pipe routes is not a major consideration although connecting other steelworks would require detailed consideration. Sheffield's steelmaking sites have a combination of EAFs, for producing the molten steel from scrap metal, and gas-fired furnaces for reheating metal products during processing.

5.2.2 Sheffield Forgemasters International Ltd. site and processes

The particular focus of this study is the Sheffield Forgemasters International Ltd (SFIL) site in the Lower Don Valley, approximately four kilometres northeast of Sheffield city centre. The River Don passes through the centre of site, see Figure 5-3, and this acts as a source of water for processes on site. An extension to Sheffield's DH system passes along the eastern edge of the site (red line in Figure 5-3) and supplies heat for a large workshop building in the centre of the site.

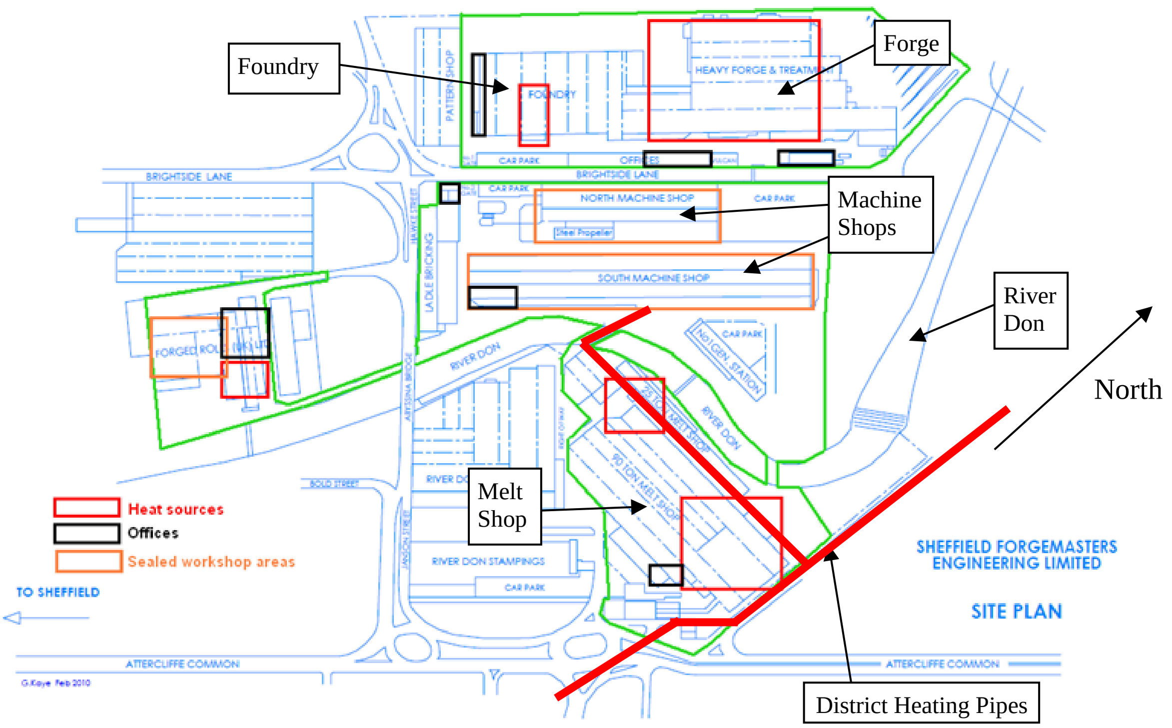

Figure 5-3: Site plan of Sheffield Forgemasters.
Source: Sheffield Forgemasters International Ltd.

There are various heat sources on site, and a meeting with SFIL's Group Environment Director in February 2013, followed by a site visit in April 2013 helped to identify the opportunities. SFIL are committed to reducing their environmental impact and implementing sustainable practices. Since 1990, the company has already reduced its greenhouse gas emissions by over 40% (East Coast and Yorkshire

Post, 2015). Koh et al. (2011) undertook a life cycle assessment for a tonne of steel ingot produced at SFIL calculating a carbon footprint of 539 kg CO_2 equivalent per tonne for the whole supply chain.

Electric arc furnace

SFIL have an alternating current electric arc furnace (EAF), with capacity to melt 100 tonnes of scrap and produce 90 tonnes of steel (SFIL, 2014). The EAF allows for a concentration of energy into a batch process, on a much smaller scale than a blast furnace meaning lower capital costs to melt down and recycle scrap steel. Around 40% of crude steel production in Europe uses the EAF method (EUROFER, 2013), but in the UK this fraction is lower at around 20% (DECC, 2015b).

Graphite electrodes are lowered into the EAF delivering high voltages and currents to heat the scrap metal to 1600-1700°C. Chemical reactions also deliver some heat including natural gas burners and oxidation reactions between oxygen added to the furnace and elements in the furnace. The SFIL EAF has a power rating of 42 MVA fed with a 33 kV supply (SFIL, 2014). The EAF cycles usually repeat through the day and night from Monday afternoon through to Thursday (SFIL, 2013).

A refractory lining protects the furnace structure from the intense heat, with low pressure cooling water circulation to keep the lining temperature down (SFIL, 2013). Cooling water leaves the arc furnace cooling system at around 30ºC, but slowing down the water flow could raise this to 60 or 70ºC (*ibid.*).

Smoke and dust generated as hot flue gases during heating are captured by a flue and carried off to a filtering plant. The flue gas primary extraction duct is shown in Figure 5-5. There is also a roof-level extraction canopy in the furnace area of the Melt Shop building to capture dust and smoke that escapes.

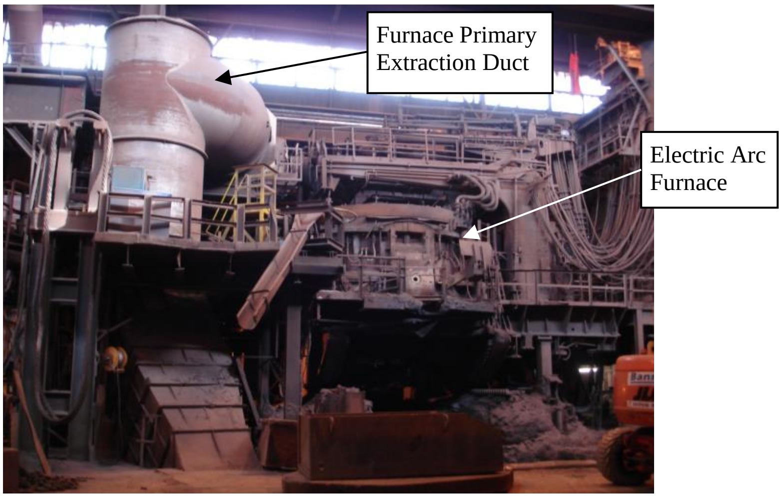

Figure 5-4: Electric Arc Furnace at Sheffield Forgemasters International Ltd.
Source: Photograph taken during site visit with permission.

Figure 5-5: The Electric Arc Furnace during operation.
Sources: (top) photograph taken during site visit; (bottom) The Star (2013).

Reheat furnaces

The reheating furnaces on site are all gas-fired and there are two main types of furnace: ‘top hat’ and ‘bogie hearth’. The metal can be heated up to 1270°C or up to 650°C in the top-hat furnaces (SFIL, 2014). The top hat furnace containment can lift off, hence the name; their small flue vents would make it difficult to incorporate heat capture equipment. The bogie hearth furnaces are usually fixed construction, with a bed on which metal products for heating lie, as shown in Figure 5-6. The bed is pushed along rails through the open furnace door and this door is shut before heating.

Figure 5-6: An example bogie hearth furnace.
Source: Steel-Technology.com (2013)

Since 2007, SFIL has spent in excess of £3 million in modern burner technology to boost efficiency (SFIL, 2012). Regenerative burners on site use a bed of ceramic material to capture heat from exhaust gases leaving the furnace. The burners operate in pairs and alternate through time, working cyclically in opposing directions so that the heat gained from exhaust gases is passed to air entering the furnace when the direction changes (Bloom Engineering, 2013). Recuperative burners have tubes or plates to transfer heat from the exhausts back to pre-heat the combustion air without mixing the gases themselves (IIP, 2013).

The amount of sulphur dioxide in the flue gases would be important for heat recovery since this has a strong effect on gas acidity and hence any heat exchanger put in would have to be resistant to corrosion. If the gas temperature remains above the acid dew point then this is less of a concern. The emissions of aerosols due to low flue temperatures may be a cause for concern, which should be investigated before suggesting heat recovery.

Vacuum arc degassing

The vacuum arc degassing (VAD) process follows the EAF. The ladle, once filled with liquid steel from the EAF, is placed into a pit shown in Figure 5-7. The vacuum hood (also shown) is placed over the pit for the VAD process which purifies the metal. Electrodes perform heating and alloy materials are added. Oxygen may be added in the Vacuum Oxygen Decarburisation variation of this process to remove impurities, and oxidation reactions will add heat. The VAD equipment uses a steam jet ejector to create the vacuum. Inter-condensers fed with cooling water are needed between a series of steam jet ejectors to reduce the mass flows and allow effective operation (ec21.com, n.d); heat from the inter-condensers is transferred to cooling towers on the site, shown in Figure 5-8.

Figure 5-7: A ladle of molten steel in the vacuum degassing pit.
Source: Sheffield Forgemasters (2014).

Four steam boilers generate the high pressure steam needed to power the steam jet ejector. These boilers run continuously over four days while the EAF is active and steam is stored in a 90 tonne steam accumulator at up to 34 bar until required for rapid discharge over 20 minutes to create the vacuum underneath the vacuum hood shown in Figure 5-7 which is moved into place over the vacuum pit.

Figure 5-8: The three-cell cooling tower at the back of the Melt Shop.
Source: photograph taken during site visit.

5.3 Heat recovery and storage potential assessment

After consulting Sheffield Forgemasters and visiting their site, it was considered that there could be potential to recover heat from the flue gases originating from the electric arc furnace, together with flue gases on the gas furnaces where some heat recovery already occurs, and from cooling systems in the Melt Shop. A more detailed review of the potential heat sources was undertaken to understand typical patterns of heat production and quantities of waste heat.

5.3.1 Electric arc furnace (EAF)

The amount of electrical and other energy inputs (oxygen, natural gas, carbon) will vary from furnace to furnace and between different melts in the same furnace depending on the amount and type of scrap metal used. In this case study, the energy consumption figures were not available for commercial reasons, hence typical figures required for the analysis have been sought from the literature. The majority of heat input is from electricity, but there are also significant chemical energy inputs (mainly oxygen and natural gas) as shown in Sankey diagrams of Figure 5-9 for typical EAF operations.

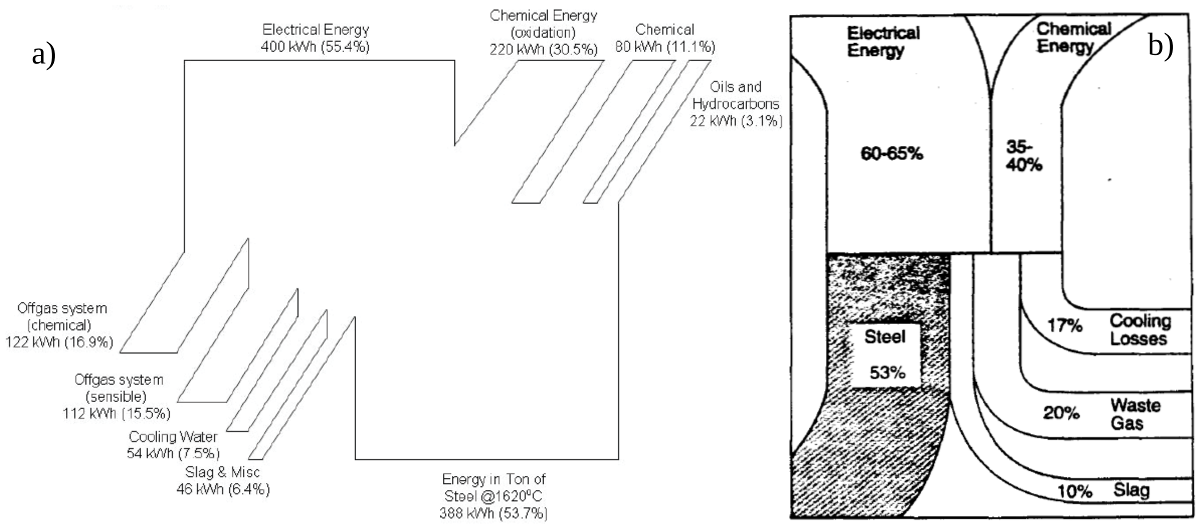

Figure 5-9: Energy balances for a typical modern electric arc furnace.
Sources: (a) Schliephake et al. (2011); (b) Jones (1997).

Around 50- 55% of the energy input leaves as sensible heat energy in the steel and Figure 5-9 (a) shows that around half of the energy escaping in the off-gas is chemical energy, mainly carbon monoxide and hydrogen produced in the furnace. Higher electrical inputs for some furnaces are often due to the lower use of oxygen (Jones, 1997). Figures for electricity consumption from the literature show some variation with examples given in Table 5-1.

Table 5-1: Electrical energy input for electric arc furnaces.
Note: tls = tonne of liquid steel output.

Arc furnace electrical energy input (kWh/tls)	Reference
404 – 748	European Commission (2013)
360 – 400	Jones (1997)
560 – 680	Environment Agency (2004)
400	Zuliani et al. (2010)

The UK's four EAF sites are listed in Table 5-2 with their production capacities, recent actual production, and 2004 carbon dioxide emissions figures. Together, the EAF sites in Sheffield and Rotherham produce over a million tonnes of steel per year. The UK produced 1,942,000 tonnes of crude steel via the EAF route in 2013 (Worldsteel Association, 2014), equivalent to 51% of the overall production capacity listed in Table 5-2.

Table 5-2: Electric Arc Furnace plants in the UK with production and emission statistics.
Source: Capacities from McKenna (2009), emissions from Entec (2006), production levels from Koh et al. (2011), ABB (2011), ABB (2014) and Celsa (2012).

Operator	Melt Shop capacity (kt/year)	Melt Shop recent production (kt/year)	CO_2 Emissions in 2004 (kt CO_2/year)
Celsa UK, Cardiff	1,200	1,140	101,500*
Outokumpu, Sheffield	540	260	50,800
Tata Steel**, Rotherham	1,250	750	298,649
Forgemasters, Sheffield	130	60.2	69,162
Total	3,840	2,210	550,877

* - Since 2006 rebuild, new off-gas analysis saves 18,000 t CO_2/year (Celsa, 2012). ** – Formerly Corus UK Ltd.

Dryden (1975) illustrated a typical power input programme for an arc furnace as shown in Figure 5-10. The suspension of power input is usually to allow the addition of more scrap to the furnace or for sampling of the steel to occur. Dynamic energy balance models were generated by Kleimt et al. (2005) showing the energy losses to each waste heat stream including cooling water and their variation though time. Example results for one modelled cycle are shown in Figure 5-11 and Figure 5-12.

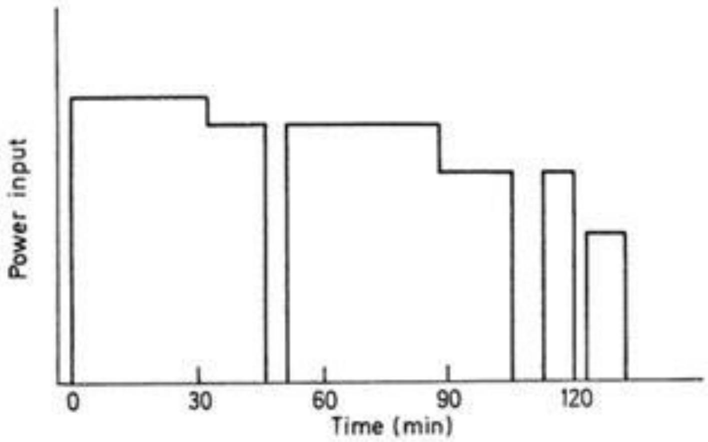

Figure 5-10: Typical power input programme for an arc furnace.
Source: Dryden (1975).

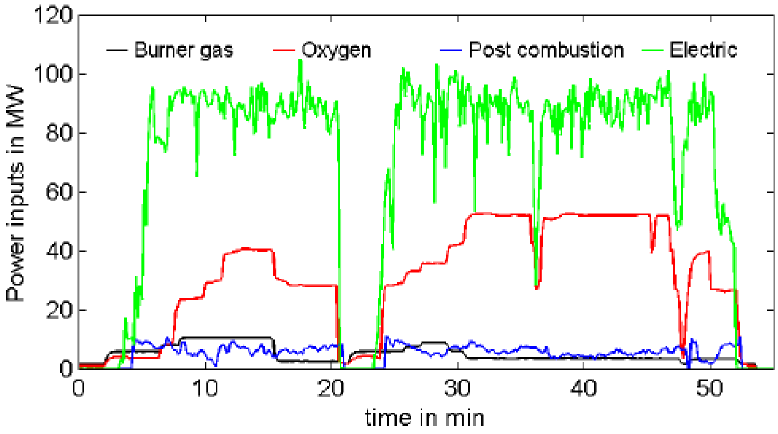

Figure 5-11: Modelled energy inputs for an arc furnace cycle.
Source: Kleimt et al. (2005).

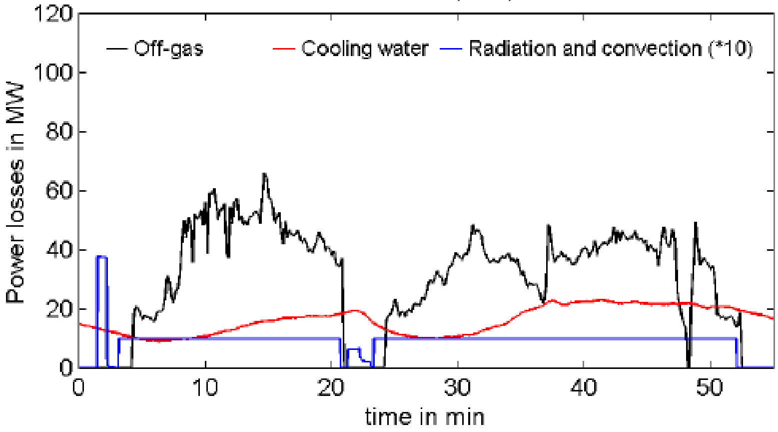

Figure 5-12: Modelled energy output variation for an arc furnace cycle.
Source: Kleimt et al. (2005).

EAF flue gases

A schematic of the de-dusting system for the EAF is shown in Figure 5-13, with most of the flue gas flowing to a primary duct while escaping gases are captured by an extraction canopy inside the building. Gas velocities in the main duct can be up to 40 m/s while the secondary duct can capture as much as 30% of the flue gas energy (Kirschen et al., 2006). There can be a heavy dust load in the off-gas fumes from 9.5g/m^3 (Brandt et al., 2014) up to 200 g/m^3 (Dixon and Bramfoot, 1985) before flue gases reach the on-site plant for filtering and treatment.

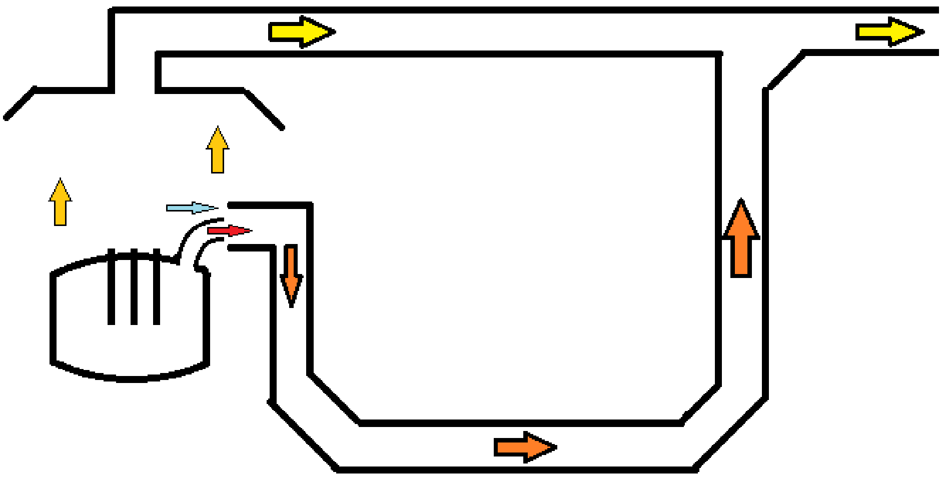

Figure 5-13: The arc furnace de-dusting system showing direction of flue gases towards the gas treatment facility.

The amount of oxygen and natural gas injected into the furnace has a big effect on the volume of off-gases and so is important for energy losses and heat recovery (Pfeifer and Kirschen, 2002). Temperature peaks for off-gas correlate with concentration of carbon monoxide and the occurrence of post-combustion reactions described by equations 3.16 and 5.55 (Kirschen et al., 2006). Post-combustion of gases leaving the furnace can liberate some of this chemical energy raising it to well over 25% of the energy input (Zuliani et al, 2010).

$$CO + 0.5O_2 \rightarrow CO_2 \quad \Delta H = -282.98 \text{ kJ/mol} \tag{5.54}$$

$$H_2 + 0.5O_2 \rightarrow H_2O \quad \Delta H = -241.81 \text{ kJ/mol} \tag{5.55}$$

Born and Granderath (2013b) estimate that off gases contain 170 to 240 kWh of energy per tonne of liquid steel depending upon the level of chemical energy input (i.e. natural gas and oxygen injection volumes). Further details on flue gas properties are noted by Brand et al. (2014).

Conventional EAFs have water-cooled flue ducts that bring gas temperatures down to around 700°C (Zuliani et al., 2010); one such system uses pressurised hot water at 220°C and 23 bars for evaporative cooling to recover 30-37 kWh energy per tonne of steel with high efficiency (Kirschen et al., 2006). Most steelworks inject water spray into the flue gas while others inject excess air to lower the temperature and reduce the risk of dioxin production (Born and Granderath, 2013b). The solution chosen depends on various factors including the filtering methods used for dust capture (Kirschen et al., 2006).

Dixon and Bramfoot (1985) recorded temperatures in a UK-based EAF flue duct over a melt lasting approximately two hours. The gas temperatures were highly variable as shown in the first graph of Figure 5-14. The period of low flue gas temperatures around 50 minutes corresponds to the adding of a second basket of scrap metal (*ibid.*). The melting practice will vary between different steel mills and perhaps between melts.

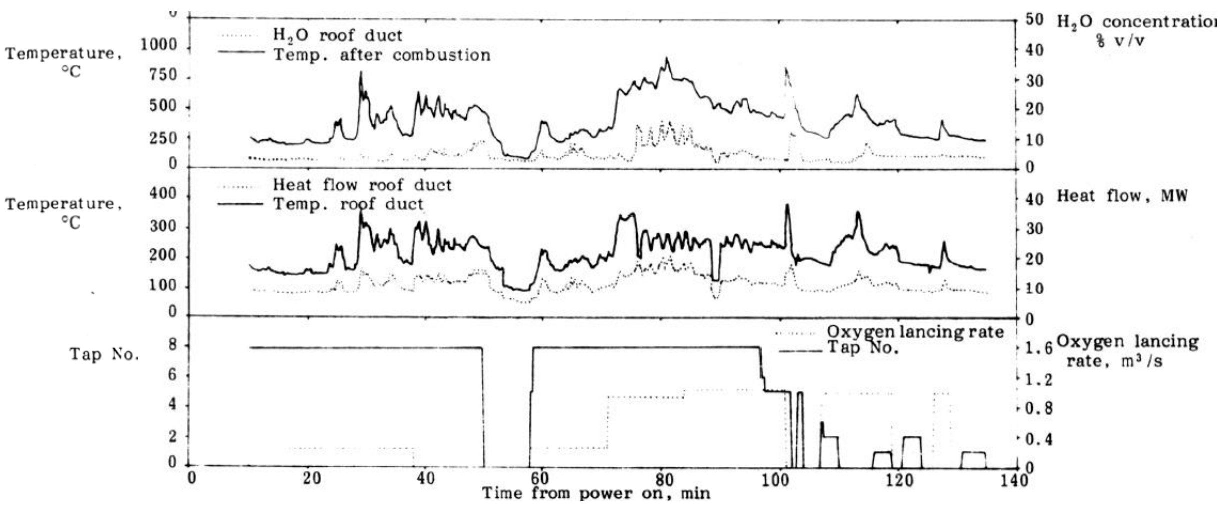

Figure 5-14: Measured flue gas properties during a cycle of a 180t British Steel furnace.
Source: Dixon and Bramfoot (1985).

EAF scrap preheating

Commonly, but not in the UK, the sensible heat in the EAF off-gas is used to preheat scrap to around 800°C; this can save 100 kWh of energy consumption per tonne of steel produced (European Commission, 2013). It lowers energy inputs by 15-20%, and helps to achieve shorter furnace cycle times (Jones, 1997). Scrap preheating can cause problems with formation of dioxin gases from warm scrap metal. A residence time for off gases of at least two seconds over 800°C with oxygen over 6% is deemed necessary to destroy dioxins, with the chance of reformation between 550 and 250°C if cooling rate is below 300°C/s (Frittella et al., 2015). The mechanisms for reformation were identified by Taylor and Lenoir (2001).

Scrap preheating techniques include basket preheaters, the rotary kiln process and the twin shell method (Bramfoot et al., 1985). Experience has shown the need to avoid overheating of the scrap basket to prevent welding and bridging in the charge (*ibid.*) and the savings represent some 10 to 25% of the energy in the flue gas. Reasons for not preheating scrap can include inconvenience in the shape of scrap and concerns over side-effects on the treatment of furnace off-gases.

EAF cooling water

Recovering heat from cooling water will usually require the use of heat pumps to raise temperatures, as explained in Section 5.3.4. However, there are examples where heat exchangers have been used to direct heat from cooling water to DH. For example, in Graz, Austria heat is recovered from a gas-fired reheat furnace and cooling water at around 90°C from two electric arc furnaces (Schlemmer, 2011). This project was recovering 40 GWh of heat per year, and with a 67m^3 buffer this could be raised to 60 GWh per year (*ibid.*). One foundry in Alvesta, Sweden is using a lower-temperature parallel DH network in order to deliver 7-8 GWh of heat caught from cooling towers as metals cool (SFS AB, 2002).

5.3.2 Reheat furnaces

Gas furnaces use lower temperatures than the EAF and the metal is not melted again in this process. Water-based cooling is only needed to protect some furnace parts such as the rollers or furnace door. Figure 5-15 shows the energy flows for a furnace without heat recovery, and Table 5-3 quantifies those figures as percentages. Si et al. (2011) investigate the benefit of capturing some of the flue gas heat to preheat metal ingots.

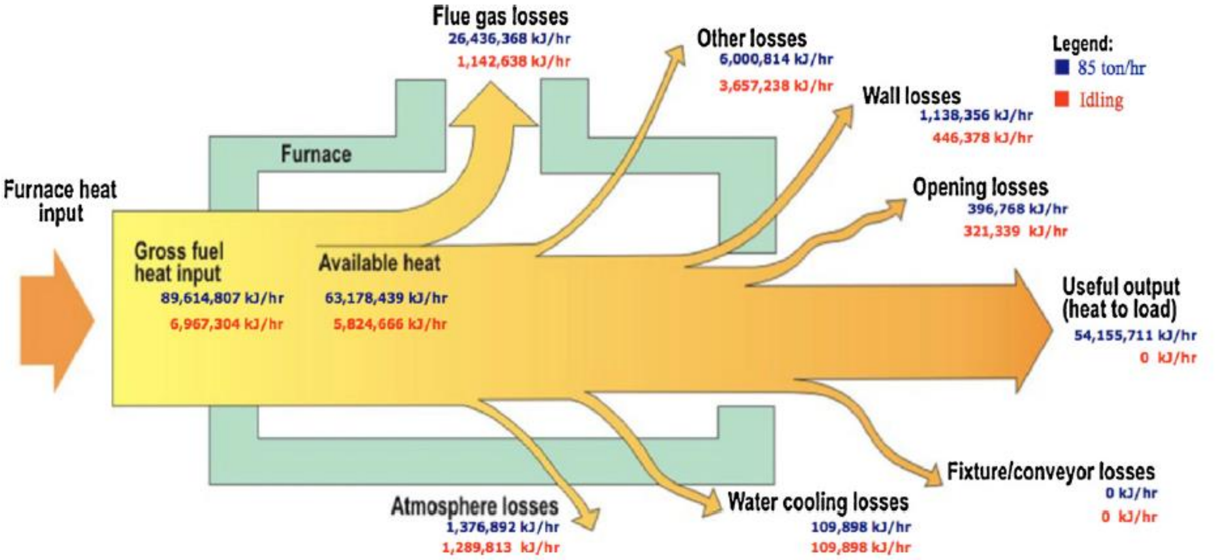

Figure 5-15: Energy flows for a furnace heating 85t of steel per hour and under idling conditions. Source: Si et al. (2011).

Table 5-3: The percentage energy losses from a gas furnace without heat recovery as stated by Si et al. (2011).

	Processing 85 t/h (% energy output)	Idling (% energy output)
Useful output (heat to load)	60.4	-
Flue gas losses	29.5	16.4
Atmosphere losses	1.5	18.5
Wall losses	1.3	6.4
Opening losses	0.4	4.6
Water cooling losses	0.1	1.6
Other losses	6.7	52.5

Modern furnaces tend to use recuperator and regenerator devices but this approach can increase NO_x production (Tenova Group, 2014). Regenerators are unsuitable for the arc furnace due to high dust loads in the flue gas which would clog the regenerator. Also, since arc furnace energy input is largely electrical rather than combustion, the influx of air is not required to be large and hence passing heat to incoming air is less practical.

Recuperator systems are an alternative for exchanging heat from exhaust air with incoming air; this technology involves using a heat exchanger and the heat is not stored. Such units operate continuously (Dryden, 1975) rather than the reversals seen for regenerators. With a recuperator recovering some heat, approximately 21% of the input energy leaves via the stack as shown in Figure 5-16 (Tenova Group, 2014).

Flue gas temperatures depend upon the amount of air that has entered the process and also the stage that heating the metal is at. With gas-fired furnaces there is an optimum stoichiometric (chemically balanced) ratio of the amount of combustion air per unit of natural gas burned. This ratio is around 10 to 1 and exhaust temperatures fall as the excess air ratio increases (DoE, 2004).

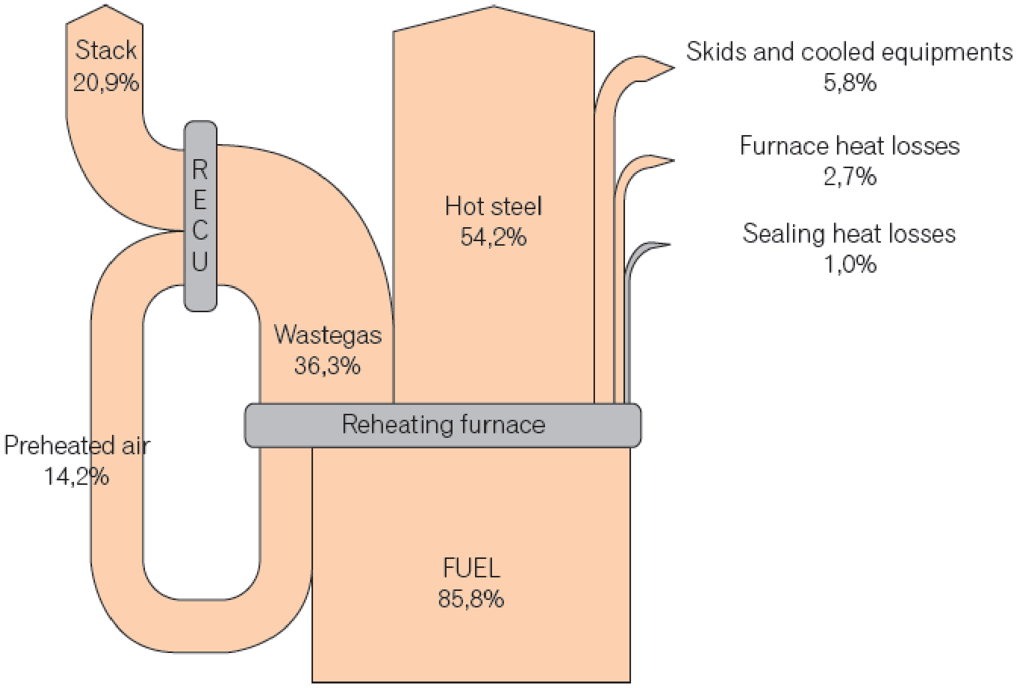

Figure 5-16: Sankey diagram of the energy flows in a gas fired furnace fitted with a recuperator. Source: Tenova Group (2014).

Case study evaluation

Annual energy consumption figures for each gas furnace were provided and these were used to estimate recoverable quantities of heat. There are around 20 furnaces on site, but some are used much more frequently than others so it would only probably be cost-effective to use a small number of them. Maximum fuel burn rate equates to around 10 MW on large furnaces (SFIL, 2013). Sheffield Forgemasters consumes over 8 million therms (234 GWh) of gas per year (Gazprom Energy, 2013).

SFIL provided data regarding gas furnace energy consumption in 2012. With 20% of the input energy leaving through the stack when a recuperator is fitted; perhaps 10% of the input energy can be recovered. Steam could be recovered at high pressure (30 bar, 234ºC) as well as heat for DH, but having two separate heat exchangers on two furnaces as well as separate steam and DH pipes across the site would be cumbersome and therefore only DH production is considered from these furnaces. Heat recovery from the gas furnaces may be simpler than with the arc furnace as the flues will not be as dusty, a figure of 9.5% recovery of the input heat was considered applied to two furnaces with highest energy consumption resulting in 4000MWh of heat being available for district heating.

5.3.3 Waste heat boilers

High waste heat temperatures could generate high pressure steam for industrial processes or for electricity generation. Waste heat boilers would have to resist corrosive chemicals in the flue, such as hydrogen chloride (HCl) gas, and maintenance and cleaning regimes will be required to prevent dust accretion from significantly reducing the heat transfer rates. Added resistance to air flow from heat exchangers may result in greater settling of the dust. Heat pipe technology, as featured in Section 3.1.9, could reduce difficulty due to dust by allowing smaller exchange surfaces with much greater effective thermal conductivities (Ammar et al., 2012).

Feasibility studies

Bramfoot et al. (1985) investigated potential waste heat boilers in the EAF flue duct, finding a payback time of less than two years for a waste heat boiler, but that study did not investigate the possibility of using heat for DH. Dixon and Bramfoot (1985) gave more details on the study finding that the gases are hot enough to run a steam-powered electricity turbine, but found that this use was not economic. Bramfoot et al. (1985) suggested a steam tube boiler since the cooler operation temperature of a water-cooled system may affect the dust deposit level.

Implemented examples

Figure 5-17 shows a heat recovery system implemented on an EAF duct generating steam and hot water. Steam generation has nearly eliminated gas boiler use for on-site steam production (Schliephake et al., 2011). This project took 15 months to implement on a 140t/h tapping weight furnace, producing 12t/h of saturated steam at 13-20.5 bar (Tenova Group, 2014). Around 25% of the steam generated from the furnace is used for vacuum degassing (Born and Granderath, 2013b). This EAF recovery project stated that their technology recovers up to 70% of the heat in off-gases (Tenova, 2011).

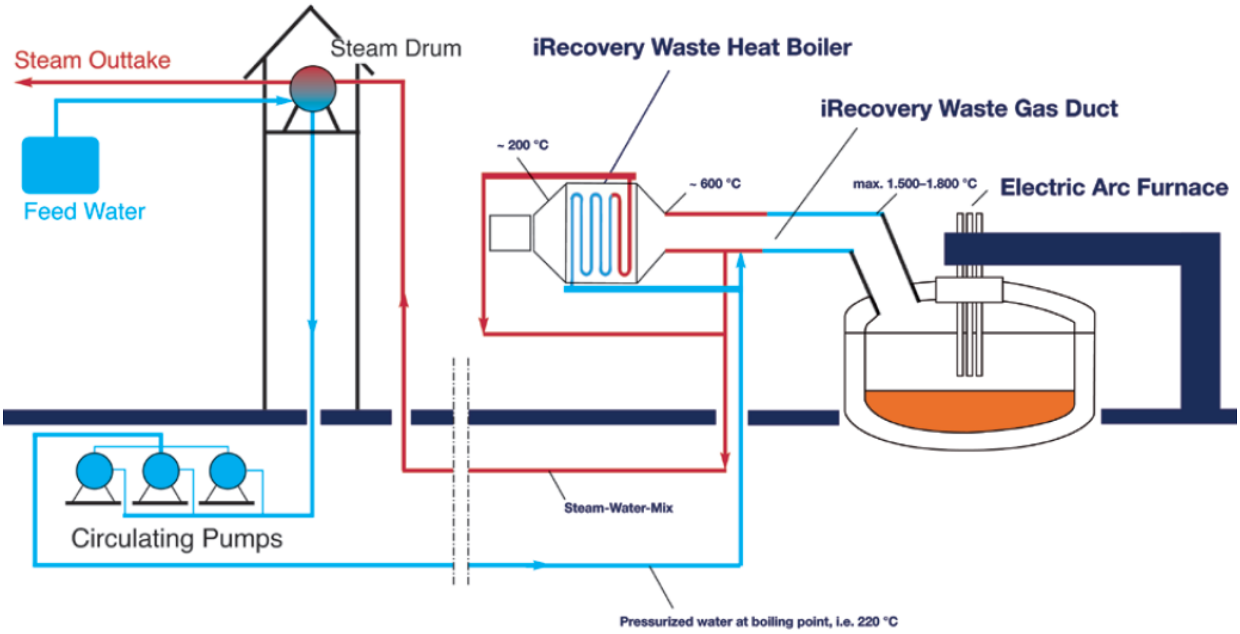

Figure 5-17: Tenova iRecovery System developed in Germany.
Source: Schliephake et al. (2011).

Kirschen et al. (2006) found 179kWh/tls transferred to a high-temperature liquid water (220°C, 23bar) gas duct cooling system (representing 22.9% of the total energy), compared with 101-123 kWh/tls for the low-temperature water cooling (30-50°C), however the gases still left this duct at 500-750°C and the system is designed to cool the gas down to protect the duct rather than for purposes of energy recovery. Zuliani et al. (2010) state that a 140t/hr EAF has produced 20t/hr of steam on average, and combining with a waste heat boiler some 75-80% of the off-gas energy is recovered, lowering the flue gas to 200°C. Flue gas heat recovery on a 100 tonne cold water-cooled EAF was found to save 123 kWh/tls (Kirschen et al., 2006) while another example recovered 139 kWh/tls (Born and Granderath, 2013b).

A figure of 125kWh/tls (just under 0.75 x 170) is used as an estimate for recoverable energy from the arc furnace flue in this case study assessment.

Most recently, there has been a further plan developed to link a steel plant to DH in Brescia, Italy. The proposed system will involve waste heat at 600°C for an Organic Rankine Cycle for electricity generation (pitagoras.eu, 2015), a Consteel process for scrap pre-heating, and contribution of heat to DH (SiderWeb, 2014). The industrial partner is contributing €12 million, and the European Commission is contributing €2.5 million (Bresciaoggi.it, 2014) as part of a project which is also demonstrating the use of a large hot water store (40,000m^3) for seasonal energy storage (pitagorasproject.eu, 2015).

Organic Rankine Cycles and Kalina Cycles

At medium temperatures, low-pressure steam and/or hot water can generate electricity in an Organic Rankine Cycle (ORC) with efficiencies of around 20% (Zuliani et al., 2010). To justify electricity generation, a reasonably continuous supply of heat is necessary. Furthermore, an ORC electrical output of 0.5 MW is likely to be the minimum cost-effective size (Hammond and Norman, 2014). As of April 2014, manufacturer Turboden had 230 ORC plants of which seven were operating from industrial heat recovery in an output range of 0.5-7 MW (Bause et al., 2014).

The case for generating process steam or heating water usually provides better paybacks than electricity generation (Born and Granderath, 2013). At the Feralpi plant, the sale of steam (10t/h) to a nearby tyre factory has proven more profitable than using the ORC (20t/h) (Born and Granderath, 2013b). The system uses steam at 27 bar and 245°C to supply heat to a 2.7 MW ORC generator consuming 20 GWh out of a total of 150 GWh of heat recovered (Tenova Group, 2014b).

Kalina cycles are a similar technology, using water-ammonia as working fluid; examples of use of both Kalina and Organic Rakine Cycles are given by Haddad et al. (2014). Process intermittency and lower heat production volumes meant that these cycles were not considered for implementation at the case study steelworks.

5.3.4 Heat pumps

Frederiksen and Werner (2013) state that the Coefficient of Performance (CoP), as described in Equation 3.13, can reach a value of up to 8 if the waste heat source is at a high temperature. EDF are developing heat pumps which can be used by industry to convert waste heat sources typically at 40°C to supply at 100°C with a CoP of 5 quoted (EDF, 2013).

Sheffield's DH supplies heat at 110˚C and delivery of heat from heat pumps at this temperature is difficult and suitable technology is at an early stage, as described in Section 2.1.3. Incorporation of heat from the heat pump to the network may be possible by adjusting the CHP unit to produce higher temperature heat to mix in with lower temperature heat from the heat pump, or a gas boiler may be required to top-up the temperature. Variations of more than a few degrees from the standard temperature setting may cause thermal stresses on the network.

The source of heat in the case study could be around 60°C but higher temperature of delivery to DH would be required. Since absorption heat pumps are a less widely used technology, with generally lower CoPs, a mechanical vapour compression heat pump is assumed. Delivery of heat to the heat network is assumed to achieve CoP of 5.0.

5.3.5 Heat storage for this case study

Following from the discussion of Section 3.5, heat storage can also be implemented to manage the production of waste heat in this case study. Since useful heat can be generated as steam (for use on-site) and as DH water (for use in buildings on the network), hot water and steam accumulators are considered. The volumes of DH water produced are small relative to annual heat consumption of the network and therefore can be integrated to the heat network without the need for seasonal heat storage. If multiple steelworks were to connect then there might be benefit using in seasonal storage.

Hot water accumulators

Hot water accumulator technology was reviewed in Section 2.5.1, while the use of other technologies in the mid-temperature range were excluded in Section 3.5. Hot water accumulators can help control the supply of waste heat to DH, and it can also serve the other heat sources on the network. If industrial cooling water is to be used as the source for a water-source heat pump then this may need to be stored as well. Hot water tanks can achieve high energy charge and discharge rates as shown in the Literature Review.

In Sheffield, a store could be hydraulically linked to DH and would need to be pressurised in order to operate at the 70-110°C temperature range of the network. There are spatial factors relating to the position of the heat storage within the network as pipeline diameters affect the charging capacity as described in Section 4.3.4. Store capacities of 10 MWh (250 m^3) and 20 MWh (500 m^3) are considered for the main scenarios although some other values are also trialled.

Steam accumulators

Generation of high temperature steam can be used to pass heat from one process to another and saturated steam can be stored in a steam accumulator. Lower temperature and pressure steam is less useful for industrial processes or power generation but could be stored in the same way then directed towards DH supply. Such accumulators are already widely used to balance steam production and consumption by industry. In this case study, the on-site steam accumulator is considered to be sufficient and no extra investment for steam recovery or storage is modelled.

5.4 Energy system modelling

A novel computer model was developed to simulate the performance of the heat sources and heat storage in the case study. The flexibility of the model allows for parameters to be investigated, particularly varying the amount of heat storage and the amount of heat recovered. This original contribution to the literature will inform stakeholders regarding the best approach to heat recovery, in particular which waste heat sources to prioritise and the benefits of various heat storage volumes. The model could be adapted to other case studies elsewhere in the UK. The model could also be used in other countries but the income from both electricity market and any incentives would need to be adapted.

The model comes in two parts: the base scenario energy system model represents the flow of heat from different sources into the network using heat demand records and a simulation of CHP unit availability; the second part allows various capacities of heat storage to be implemented and determine revenues. Where storage is present, a store operation algorithm is applied to fulfil three main objectives:

- integrate industrial waste heat into the heat network (use low cost heat by avoiding loss of heat to environment);
- to reduce the use of gas boilers (representing the highest heat cost); and
- adjust CHP heat production timing allowing higher electricity outputs during higher electricity price periods.

The operational algorithm is described in detail in Section 5.4.8. The program was written in C++ language, then compiled and run using the University of Sheffield’s Iceberg computing facility. The program generates the technical, environmental and economic outputs of the heat recovery and storage systems under different scenarios of heat recovery application and heat store capacities.

Further calculations were carried out in Microsoft Excel to calculate:

- cost savings from reduced gas boiler use (both for industry and DH);
- costs of carbon taxes;
- the economic and environmental effects of operation of a heat pump;
- reductions in cooling water use;
- the sensitivity to different grid electricity carbon intensities; and
- future cost variations under different price scenarios.

The following parts of Section 5.4 describe the detailed approach to each of the system components from a technical perspective. Then the economic and environmental assessments are described in Sections 5.5 and 5.6 respectively.

The interaction of heat sources even without storage is complex, for example as shown in Figure 5-18. The first part of the computer model calculates the contribution of the different heat sources in each half-hour interval without heat storage.

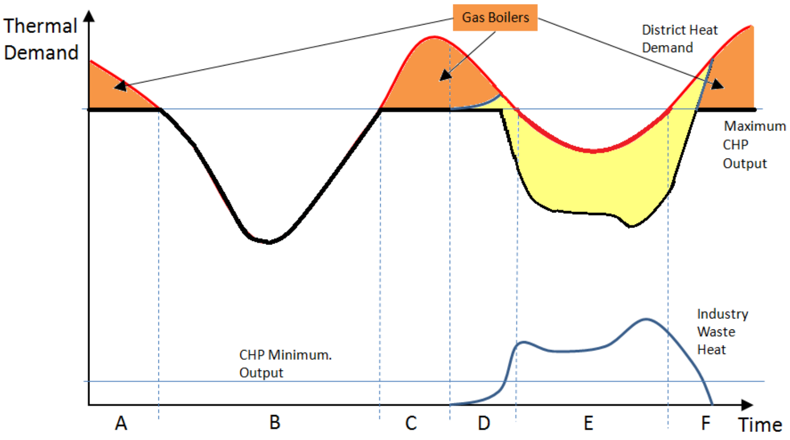

Figure 5-18: Variation of heat sources. CHP heat output follows black line when industrial heat has priority.

5.4.1 Heat network demand

Since Sheffield's new heat network is at the early stages of development, it is difficult to predict the nature of heat demand that will develop by the time a heat recovery project could be active. The half-hourly variation of heat demand on the network during a year was simulated using a data set of heat consumption readings from 33 buildings in the University of Sheffield. The data covered July 2012 to June 2013, and further detail on this data is given in Chapter 4. The readings were multiplied by a factor of approximately 4.5 to give an overall annual demand of 120,000 MWh. This is the approximate demand level expected once the new network is fully developed (EON UK, 2014). The data is used in the model to represent the network load, including both heat demand and heat losses on the network. The network heat load variation is shown in Figure 5-19.

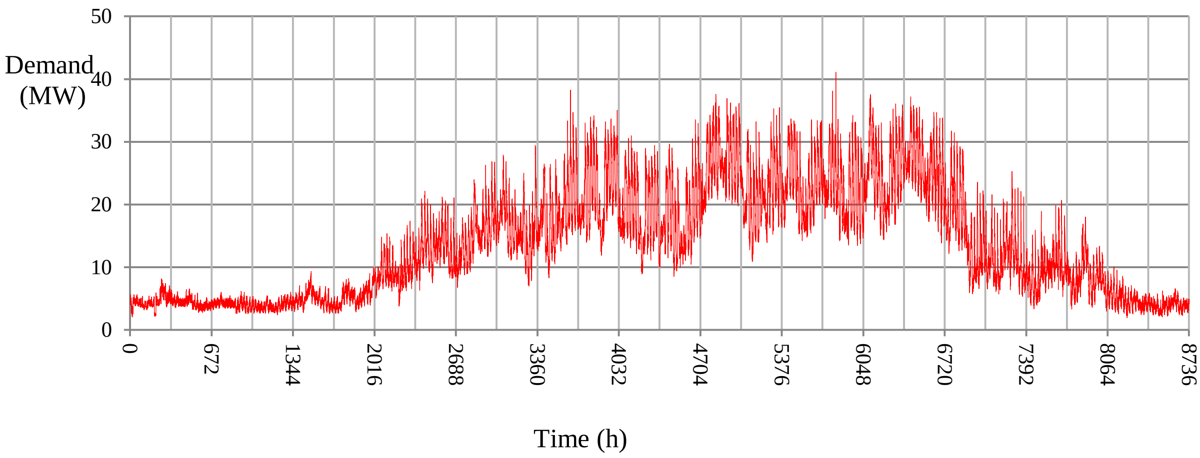

Figure 5-19: The half-hourly heat demand variation in the model.

5.4.2 Waste heat production

The program models production and consumption of heat at a half-hourly resolution. The patterns of waste heat production were understood through dialogue with the industrial site operators concerning operational cycles, as well as a literature search as detailed in section 5.3.

The program accepts the heat production pattern as a string of numbers in a file which can be modified separately from the program. Each row in the file represents a day of the week and the values are normalised in order to match annual levels of heat recovered from various sources. Another file carries

52 values defining which weeks of the year industry is running; this allows for weeks when the plant is not operational due to maintenance and there will also be variability according to the amount of steel production occurring; these files are copied in Appendix 10.5.2.

Different uses of the heat at different parts of site were considered and are summarised in Table 5-4; the heat sources are flue gases (at high temperatures) and cooling water (low temperatures).

Table 5-4: The main features of heat sources on an electric arc steelworks.

Heat source	Features
Electric Arc Furnace (EAF)	• A lot of heat is carried off at high temperatures in the flue gases (Jones, 1997) (Zuliani et al, 2010). • Waste gas stream is dusty, but such problems have been overcome to recover waste incinerator heat. • 125 kWh/tls is assumed recoverable.
Gas fired reheat furnaces	• Maximum fuel burn rate equates to around 10 MW on large furnaces. • Furnaces with recuperators lose around 24% of energy input via the exhaust (Tenova Group, 2014). • A heat recovery of 9.5% of the input energy is assumed. • Bringing the exhaust gas to temperatures below 150°C increases risk of heat exchanger corrosion.
Cooling systems	• Water cooling systems assist the steam jet ejectors and protect the lining of the arc furnace. • Cooling towers dissipate some of this heat, as does river water subject to environmental permitting constraints. • 7 to 17% of energy input to arc furnace leaves through cooling water (Jones, 1997) (Zuliani et al, 2010). • 70 kWh/tls is assumed recoverable.

The scenarios in Table 5-5 show energy recovery firstly separately from the three different sources: EAF flue gas, Gas furnace flue gas, and EAF cooling water. A coefficient of performance of 5.0 is applied to calculate the contributed energy for the DH using a heat pump to recover heat from cooling water.

Table 5-5: Captured volumes of heat used in model scenarios.

Scenario	EAF Flue Recovery (MWh/a)		Gas Furnace Flue Recovery (MWh/a)	Cooling Water Heat Recovery (MWh/a)	Heat pump output (MWh/a)	Total district heating production (MWh/a)
	DH	Steam				
Baseline	-	-	-	-	-	-
EAF	5525	2000	-	-	-	5525
Gas furnace	-	-	4000	-	-	4000
EAF cooling	-	-	-	4215	5270	5270
All	5525	2000	4000	4215	5270	14795

5.4.3 Combined heat and power (CHP)

The CHP unit supplying heat to the network considered in this study is fed by waste wood and operates with an extraction-condensing steam turbine which operates as shown in the actual design schematic in Figure 5-20. The biomass CHP unit is fuelled with approximately 250,000 tonnes of waste wood per year supplied from within 70 kilometres of the plant (The Star, 2014). The power station has 31 MW electrical capacity (Ofgem, 2014) and a thermal output of up to 25MW to the new heat network (SFIL, 2014). The use of an air-cooled condenser means that the power station does not use river water for cooling (E.ON UK, 2007). There are limits on the heat output from the CHP due to turbine design and gas-fired boilers are used to meet shortfalls in heat production, as described in section 5.4.4.

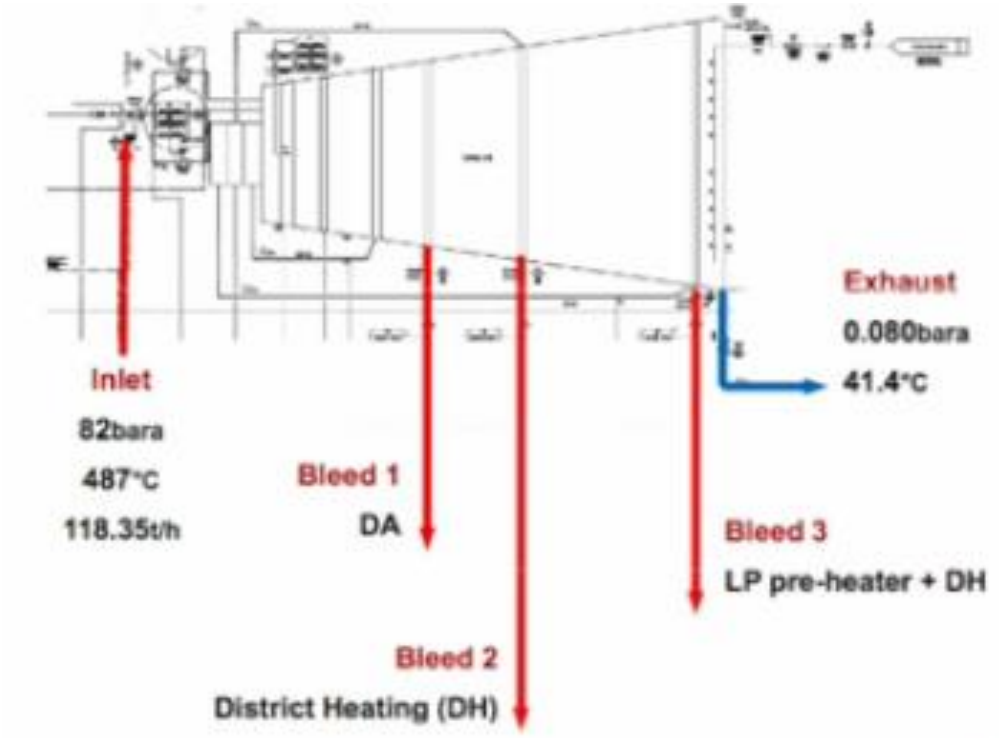

Figure 5-20: Blackburn Meadows Steam Turbine Design.
Source: E.ON UK (2015).

$$P(Q_{CHP}) = P_{eo} - Q_{CHP}/Z \tag{5.56}$$

In this case study, the CHP turbine and generator works as a base-load electricity producer and its capacity for producing heat is limited to between 1 and 25MW, therefore heat storage could also help to meet peaks in demand or prevent interruptions if demand drops below 1 MW. The maximum electricity output is 31 MW (E.ON UK, 2014). The city-centre ERF has a typical availability of 86% as discussed in Chapter 6, while the Blackburn Meadows plant on the new network is designed for an availability of around 97% (E.ON UK, 2014). The economic calculations of revenue were described in Section 3.4 and will be further detailed in Section 5.6. Some statistics regarding the two CHP plants in Sheffield are given in Table 5-6 with figures for the ERF included for comparison but only becoming relevant in Chapter 6.

Table 5-6: The CHP parameters for the two power stations in Sheffield.

CHP Site	Maximum heat output (MW)	Minimum heat output (MW)	Electricity - only capacity (MW)	Approximate primary energy input (MWh/a)	ROCs/MWh	QI Formulae Coefficients	Typical availability
Blackburn Meadows	25	1	31	920,000	1.9 (CHP) 1.5 (non-CHP)	318, 120	97%
Sheffield ERF	36	1	21	510,000	1 (CHP) 0 (non-CHP)	370, 120	86%

Outage periods were modelled through the course of the year to match the expected availabilities in Table 5-6. The length of these outage periods was also randomly chosen to fall between 12 and 72 hours. The presence of outages in the model will mean that there are periods during which the CHP cannot provide heat and therefore back-up boilers are required.

5.4.4 Gas boilers

Gas boilers are used as auxiliary heating on the DH network and are liable to charges under the EU ETS. The cost of heat production will be higher from a gas boiler than the primary CHP heat source, but the boilers allow coverage of CHP maintenance, unexpected outage or as top-up heat. The heat outputs of the gas boilers and CHP unit in the base scenario without industrial heat or heat storage is defined as in Equations 5.57 to 5.59 with total heat production always equal to demand.

Condition	Gas boiler heat output, Q_g[MW]	CHP output, Q_{CHP}[MW]	
if $Q_{DH} > Q_{CHP,max}$	$Q_{DH} - Q_{CHP,max}$	$Q_{CHP,max}$	(5.57)
if $Q_{CHP,min} < Q_{DH} < Q_{CHP,max}$	$Q_G = 0$	Q_{DH}	(5.58)
if $Q_{DH} < Q_{CHP,min}$ or CHP unavailable	Q_{DH}	0	(5.59)

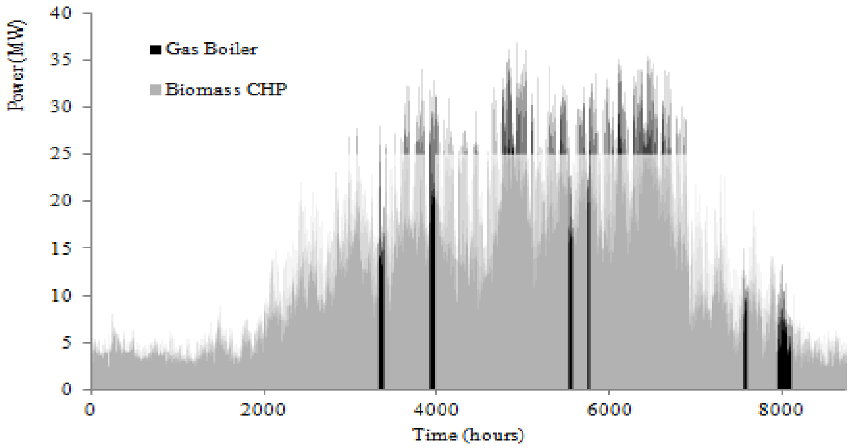

Figure 5-21: The contribution of different heat sources throughout the year in the base scenario.

5.4.5 Heat pumps

Heat pumps are required in scenarios recovering heat from cooling water to supply heat for the DH network. A vapour-compression heat pump driven by electricity is assumed, with a coefficient of performance of 5.0. At times when some heat is lost, since there is insufficient store capacity and insufficient heat demand on the network, if that heat could have come from a heat pump then it is assumed that the heat pump did not run. This assumption mainly applies when there are multiple waste heat sources available and the heat pump is the least economically and environmentally favourable. Electricity used to run the heat pump would not be required for heat lost to the environment.

5.4.6 Heat storage

Where heat is recovered at lower temperatures for DH, various quantities of hot water storage are applied at temperatures compatible with the heat network. Equations 5.60 to 5.63 show the storage capacity calculation for 100m^3 of water using water's heat capacity, c, and density, ρ, at the average temperature of 90°C (CIBSE, 2007).

$$E = m.c.\Delta T \text{ [MWh]} \quad (5.60)$$

$$E = V.\rho.c.\Delta T\text{[MWh]} \quad (5.61)$$

$$E = 100\text{m}^3 \times 965\text{kg/m}^3 \times 4.208\text{kJ/kgK} \times 40\text{K} \quad (5.62)$$

$$E = 16{,}242{,}880 \text{ kJ} = 4.51 \text{ MWh} \quad (5.63)$$

It is important to allow for some redundant space in the tank, such as a small depth at the bottom of the tank that allows for settling of any impurities, and also the unusable mixed-temperature layer where the hot and cold water meet. Overall, it is sensible to assume that around 90% of the tank's actual volume is used (Streckiene et al., 2009), therefore an energy storage density of 4 MWh per 100m^3 is assumed. This study includes scenarios as in Table 5-7, with heat storage but without industrial heat recovery in order to distinguish the effects on performance.

Table 5-7: The store capacity used in the different scenarios.

	Store Volume (m^3)	Energy Capacity (MWh)
Option 1	0	0
Option 2	250	10
Option 3	500	20

The energy system model works in a mechanistic way to eliminate the loss of industrial waste heat to environment, to reduce the use of gas boilers in favour of CHP. The waste heat is considered to be the lowest marginal cost and therefore its use is maximised, the gas boilers have the highest marginal heat production cost. A final step to alter the CHP heat production timing is incorporated raise electricity revenues, in this model these price signals are gained from the spot market (ELEXON Portal, 2015), although in reality various electricity sale contracts will be used by the power station and these are confidential.

During algorithm development, effective control strategies were found to require a good advance prediction of waste heat production and heat demand variation. The algorithm proceeds in the sequence detailed in section 5.4.8, with scenarios of differing patterns and quantities of industrial waste heat as well as different heat store capacities. The model calculates how to arrange production during one day at a time. A perfect prediction of demand and waste heat production throughout that day and the next is used. Heat losses are incorporated into the model as described in section 5.4.7.

5.4.7 Heat losses from storage and distribution

Heat can be lost through radiation, conduction and convection mechanisms. Since the site for heat capture is close to the network the focus for heat loss calculations is on those from the tank, representing a new addition to the system, rather than those from the pipe distribution network which will only see small changes from adding heat recovery. In the future, if industrial sites further from the network are to be connected then the heat losses along those connecting pipes could be significant. If the heat is to be stored by raising water distribution temperature, then there will be increased heat loss as well.

Fourier's equation for conductive heat losses, Equation 3.16, is applied to a cylindrical surface to understand losses from a pipe or walls of a tank; this derived form is given in Equation 5.64 (Frederiksen and Werner, 2013). The heat loss from pipes, Q_L, typically has a value of 10-30 W per metre of pipe. The fluid temperature, T, is set at 110°C and 70°C to match the DH supply and return temperatures.

$$Q_L = K \cdot \pi d L \cdot (T - T_a) = 2\lambda_i \pi L \cdot (T - T_a)/\ln(D/d) \tag{5.64}$$

Equation 5.64 was applied to the hot water tank situation in order to determine the level of heat losses from the tank walls. Figure 5-22 shows the level of conduction-only wall heat losses for a 500m^3 tank and a 250m^3 tank filled with 110 °C water and 70 °C water with different insulation levels. The level of losses varies with the shape of the tank as well as the thickness of insulation, a height to diameter ratio of 3:1 was assumed. The tank design for the case study will require detailed costing of manufacture, construction and the associated running costs, which is beyond the scope of this investigation.

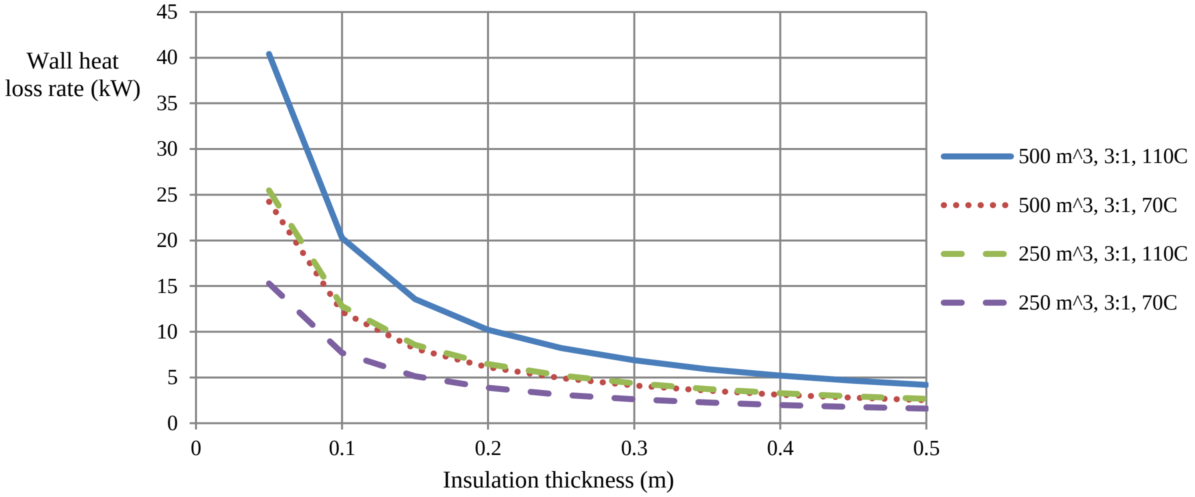

Figure 5-22: The losses from hot water tanks with differing levels of insulation.
Note: Modelled ambient temperature is 10°C. Insulation conductivity is 0.03 W/mK.

The examples of Figure 5-22 assumed a well-mixed tank that remains at the supply and return temperatures, but in reality the cooling from heat losses will cause a layer of cooler water inside the tank that will move due to higher density than neighbouring water. Usually, a small depth of water at the bottom of the tank is set aside for providing insulation effect and reduce losses from the bottom while a pocket of steam or nitrogen at the top generally reduces heat losses at the top.

The modelled heat losses are given by Equation 5.65, with a part proportional to the capacity, E_{max}, representing a constant heat loss and a part proportional to how much energy is nominally stored in the tank, $E(t)$. As an estimate, the heat losses are modelled as 15 kW from each full 10 MWh of storage and 10 kW from each store when empty with linear interpolation of heat losses between empty and full. This is including losses from the top (where there would be a nitrogen or steam pocket reducing conductivity) and the bottom of the tank (where there may be a depth of undisturbed water which broadens the temperature gradient) in addition to wall losses.

$$HL(t) = HL\_0 \times E_{max} + HL\_c \times E(t) \tag{5.65}$$

5.4.8 Store control algorithm

The complete code for the computer program is given in Appendix 10.5.3 but its sequence of functions is outlined below. The first program part calculates the base scenario without heat storage. The variability of industrial waste heat production is input as half-hour average values through the week as in the files of Appendix 10.5.2. The availability of the CHP unit, as described in Section 5.4.3, is input as a series of discrete values for each half-hour (0 = unplanned outage, 1 = available, 2 = planned outage). The amount of CHP heat and gas boiler heat is calculated each half hour, along with how much industrial heat is absorbed by the network and how much is lost to the environment.

The second part of the program introduces heat storage and carries out a sequence of operations to improve economic and environmental performance. The sequence is underpinned by the conservation of energy between heat sinks, heat store charging, and heat production as in Equation 5.66. Steps in time over which the demand, heat production and store charge rates are considered constant give heat store changes as in Equation 5.67 with *Δt* set at 0.5 hours.

$$\text{heat sinks and store charging} = \text{heat sources: } Q_{DH} + LIWH + CR = Q_{IWH} + Q_{CHP} + Q_G \quad (5.66)$$

$$E(t + \Delta t) = E(t) + (CR(t) - HL(t)) \times \Delta t \quad (5.67)$$

1. Heat losses from the store are set according to Equation 5.65, these will be recalculated as the algorithm progresses.
2. The rate of charge $CR(t)$ is limited by the capacity of the tank as in Equations 5.68 and 5.69 with a minimum charge rate necessary to make up for heat losses while the store is empty. If CR is below CR_{min} given by Equation 5.69, either lost industrial waste heat ($LIWH$) is captured, Q_{CHP} is increased, or as a last resort (highest cost) Q_G is increased.

$$\text{maximum charge rate: } CR(t)_{max} = \frac{E_{max} - E(t)}{\Delta t} + HL(t), \quad (5.68)$$

$$\text{minimum charge rate: } CR(t)_{min} = \frac{0 - E(t)}{\Delta t} + HL(t). \quad (5.69)$$

3. Then consider consecutive time periods to achieve the following objectives (subject to store limits, Equation 5.71):
   a) if CHP heat output is temporarily suspended due to low demand but CHP is available, allow continuous heat production by adding excess heat to store as in Equation 5.70.

$$\text{if } Q_{CHP} = 0\text{, set } Q_{CHP} = Q_{CHP,min} \text{ and eliminate any gas use so the change, } \Delta CR(t) = Q_{CHP,min} - Q_G, \quad (5.70)$$

$$\text{provided that } CR(t) + \Delta CR(t) \le CR(t)_{max}. \quad (5.71)$$

   b) if industrial waste heat is being lost due to insufficient demand on the network, add this excess heat to the store. The rules for this step are outlined in Equations 5.72 to 5.75:

$$\text{if } LIWH > 0 \text{ and } LIWH(t) < CR(t)_{max} - CR(t): \quad (5.72)$$

$$\Delta CR(t) = +LIWH(t), \quad LIWH(t) \to 0. \quad (5.73)$$

$$\text{if } LIWH > 0 \text{ and } LIWH(t) > CR(t)_{max} - CR(t): \quad (5.74)$$

$$CR(t) \to CR(t)_{max}, \quad \Delta LIWH(t) = -(CR(t)_{max} - CR(t)). \quad (5.75)$$

   c) if gas boilers are supplying heat while there is energy in the store, discharge the store to displace boiler use. The rules for this step are outlined in Equations 5.76 to 5.79.

$$\text{if } Q_G(t) > 0\text{, and } Q_G(t) < CR(t) - CR(t)_{min}: \quad (5.76)$$

$$\Delta CR(t) = -Q_G(t), Q_G(t) = 0. \tag{5.77}$$

else if $Q_G(t) > 0$ and $Q_G(t) > CR(t) - CR(t)_{min}$: (5.78)

$$CR(t) \to CR(t)_{min}, \quad \Delta Q_G(t) = -(CR(t) - CR(t)_{min}). \tag{5.79}$$

4. **Day-ahead consideration.** During algorithm development it was found that planning heat store management day-by-day was restricted by the amount of energy stored at the start of the day. By using the known heat demand figures for the following day (a perfect forecast) it was possible to constrain finishing store level on current day in order to better achieve benefits from storage on the following day. The rules below generate SDE_{min} and SDE_{max} (upper and lower bounds) on the store's day-finishing level. Progressively working through periods of the next day the bounds are adjusted and if upper and lower bounds converge, the algorithm stops. The rules are applied one, then the other through the periods of the day-ahead as indicated by index k:

   a) if possible, reduce SDE_{max} to allow i) excess industrial waste heat to be added to the store, and/or ii) the CHP output to be raised to its minimum output level if it is switched off but available.
   This function is performed using the day-ahead summations from different energy contributions as defined in Equations 5.80 to 5.82. These contributions are those due to: i) lost industry waste heat that could be captured; ii) extra energy from raising the CHP to its minimum heat output; iii) the heat contributions from gas boilers that could be eliminated; and iv) the heat losses from store with the additional heat stored, as in Equation 5.83.

$$\text{SumDAL (k)}=\sum_{k=0,LIWH>0}^{k} LIWH(k)\Delta t \ \ \text{[day-ahead]} \tag{5.80}$$

$$\text{SumDACMin (k)}=\sum_{Q_{CHP}<Q_{CHP,min}}^{k} (Q_{CHP,min}(k) - Q_G(k))\,\Delta t \ \ \text{[day-ahead]} \tag{5.81}$$

$$\text{SumDAG (k)}=\sum_{k=0,Q_G>0,Q_{DH}>Q_{CHP}}^{k} Q_G(k)\Delta t \ \ \text{[day-ahead]} \tag{5.82}$$

$$\text{HighDAHL (k)}=\sum_{k=0}^{k} HL\_0 \times E_{max} \times \Delta t + HL\_c \times (SDE_{max} + \text{SumDAL(k)+SumDACMin(k)-HighDAL(k-1)-SumDAG(k)})\,\Delta t \ \ \text{[day-ahead]} \tag{5.83}$$

If the contributions that would charge the store (SumDAL + SumDACMin - HighDAHL) outweigh the discharge from displacing gas boilers (SumDAG), then set SDE_{max} to allow that extra charging as in Equation 5.84. This action is preformed provided this value for SDE_{max} lies above the value of SDE_{min} defined at that period k in the day-ahead.

$$SDE_{max} = E_{max} - (\text{SumDAL}(k) + \text{SumDACMin}(k) - \text{HighDAHL}(k) - \text{SumDAG}(k)) \tag{5.84}$$

   b) If there is insufficient opportunity to raise CHP heat outputs during the next day in advance of gas boiler use, then the SDE_{min} value could be raised meaning extra heat is stored in anticipation of this. Lost industrial waste heat added to the store will also displace gas boiler use. If the contributions that would charge the store minus the heat losses for that low store trajectory (LowDAHL) added to the energy stored by raising CHP to its maximum output (SumDACMax in Equation 5.85) minus heat losses for the extra stored energy from this last step (DACMaxHL), do not outweigh the gas use then the value of SDE_{min} is raised to the value given in Equation 5.86.

$$\text{SumDACMax(k)}=\sum_{k=0}^{k}(Q_{CHP,max}(k)-Q_{CHP}(k))\Delta t \quad \text{[day-ahead]} \tag{5.85}$$

$$SDE_{min}=\text{SumDAG}(k)-(\text{SumDAL}(k)+\text{SumDACMin}(k)+\text{SumDACMax}(k) - \text{LowDAHL}(k)-\text{DACMaxHL}(k)) \tag{5.86}$$

This process stops when k reaches its maximum value of 48, or when SDE_{min} and SDE_{max} converge.

c) The finishing value of stored energy for the current day is moved into the range (SDE_{min}, SDE_{max}) by reducing or increasing the heat outputs from the CHP where possible starting from the end of the current day, provided the stored energy remains within the bounds of the tank.

5. Eliminate periods of CHP heat supply suspension (due to low demand) by redistributing CHP heat production through the day using the store provided the CHP is available to do so.
6. Increase CHP output at one time if CHP is available, and charge the store, if this will allow discharge and corresponding reduction in gas boiler use later in the current day.
7. If there is still any lost industrial waste heat, CHP heat output is reduced earlier in the day and heat from the store is discharged, allowing excess industrial heat to be added to the store.
8. **Economic Optimisation.** Increasing electricity market revenue. This part of the algorithm works through each half-hour period of the day and seeks opportunity to charge the tank at that time with a corresponding discharge at another time depending on how long the extra heat could be stored before exceeding store limits and which periods offered the highest revenue for altered timing of energy production. The result of this is the shifting forward or backward of the heat production away from the higher electricity price periods.

The day-ahead consideration was a factor affecting multi-day optimisation modelling undertaken by the IEA (IEA, 2005b). In their model the optimisation valued the energy in the store such that at the end of the optimisation period the store was always discharged. This was a problem as future non-zero start points may perform better and the discharge at the end of the day may have been better carried out earlier. This was overcome by extending the optimisation period by at least three days to remove these effects (IEA, 2005b).

The later steps in the sequence were particularly complex to program since the store must at all times remain between its upper and lower limits of capacity. The action to change the charge rate at one point in the day needs to ensure that this does not lead the store to pass its upper or lower limits later in the day. Also important is to consistently consider the extra heat losses by raising the amount of heat stored, this involved using a factor F as in Equation 5.87 to link the amount of energy added to the store to the amount that could be later removed to return the store to its original level. This factor due to altered heat losses over a number of periods, *n*, is derived from the heat loss equation, Equation 5.65.

$$F=(1-HL\_c\times\Delta t)^{n} \tag{5.87}$$

Once the algorithm has run, the system has reached a state where the capture of industrial waste heat is maximised and the use of CHP instead of natural gas has been increased. The final step of economic optimisation ensures that CHP heat outputs are at the best possible time within the constraints of the heat store's limits, according to electricity price signals. The results shown in Figure 5-23 and Figure 5-24 are from a simulation with a 20 MWh store, here CHP operation is shaped largely by the final step of economic optimisation seeking the highest prices in the electricity spot market.

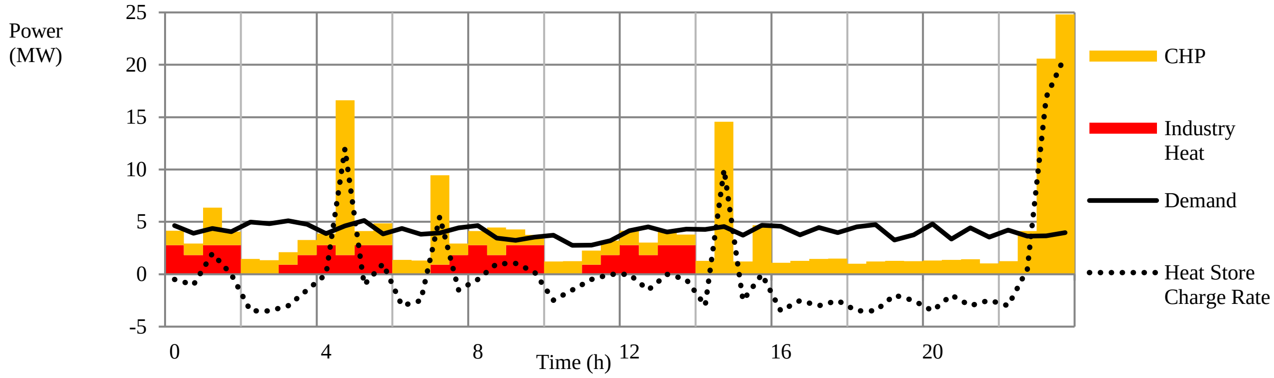

Figure 5-23: A stacked-column chart showing the variation of the heat sources, heat demand and the charge rate.

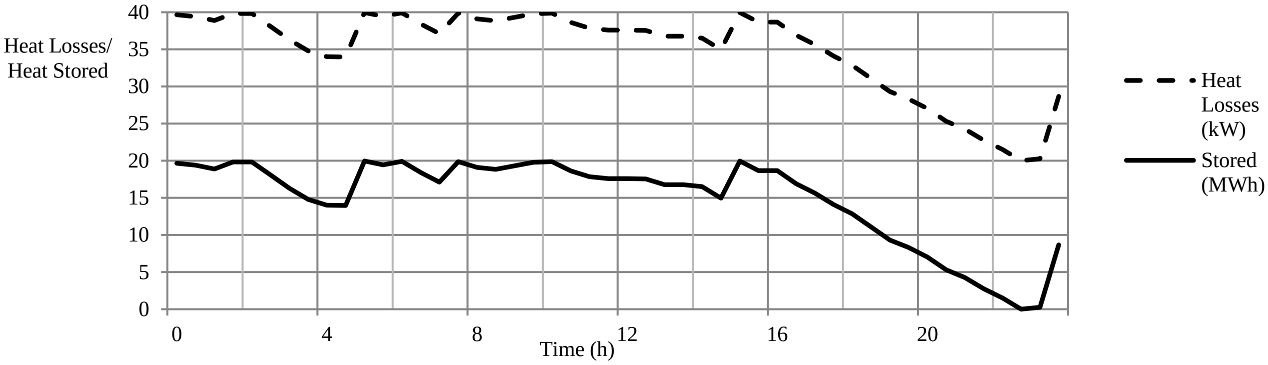

Figure 5-24: The variation of the heat store level in the scenario and time period shown in Figure 5-23 with 15 MWh of heat storage.

For the final step, the timing of heat production from the CHP is shifted into the lowest electricity price periods and the output from the CHP has a much greater range during the course of the day. The extent to which power production can be altered will depend upon the power station's parameters as well as how quickly the heat storage can be charged and discharged. If the DH water production is highly variable then this will require a quick hydraulic response from the network which may lead to fatiguing of the waste heat boiler and the network which could be problematic. It will be easier to guarantee performance if the buffer is at the industry plant so that hydraulic shocks can be prevented from travelling through the network.

5.4.9 Case study summary

In summary, a waste heat production pattern has been matched to the operation of the district heating and CHP scheme. The trade-off between heat and power for this model was expressed in Equation 3.12, with a Z-factor of 6.0 expected for this new CHP unit (E.ON UK, 2014). The new DH network running past the steelworks, shown in Figure 5-1, has a heat supply temperature fixed of 110°C while the return temperature is 70°C. Top-up heat is assumed to be from gas boilers only. Table 5-8 lists the assumptions made in the model which were built up through research as well as contact with the developers of the new CHP plant and heat network.

Table 5-8: Assumptions used in the model

Quantity	Value	Notes
Network annual heat demand	120,000 MWh	Expected demand at full build-out (E.ON UK, 2014)
CHP electricity-only output	31 MW	According to E.ON UK (2014)
CHP maximum/minimum heat output	25 MW/1 MW	Maximum according to E.ON UK (2014), 1MW assumed minimum off-take.
CHP availability	97 %	Expected according to E.ON UK (2014)
CHP start up costs	Negligible	CHP is designed to run as baseload and model will maintain a minimum heat draw from the turbine.
EAF flue heat recovery	7525 MWh	Based upon 125 kWh/tonne of steel produced
Gas furnaces heat recovery	4000 MWh	Based on 9.5% of the furnace energy input.
EAF cooling water heat recovery	4215 MWh	Based on 70kWh/tonne of steel produced
Heat store energy density	40 kWh/m^3	Based on calculation of Section 3.2.3
Heat pump coefficient of performance	5.0	Based on discussion in Section 5.3.4
Gas boiler gross efficiency	80 %	Seasonal efficiency.
Gas carbon footprint	0.18521 t-CO_2(eq)/MWh	As described in Section 3.6.1
Gas cost on GCV basis	£27/MWh	Estimated cost.
Grid electricity carbon intensity	0.449 t CO_2(eq)/MWh 0.331 t CO_2(eq)/MWh	For grid average imported electricity and marginal emissions factor for the CHP as described in section 3.6.4.
Heat pump electricity cost	£60/MWh	Estimated cost for import to energy intensive industry, actual rate is not known.
Electricity revenue	Spot Price + 1.9 ROCs/MWh	1.9 ROCs due to CHP commissioning date.
ROC value	£45/MWh	As discussed in Section 3.4.4

5.5 Environmental Analysis

Any heat recovery project needs be evaluated, not just in economic terms, but also in terms of its environmental impacts. This can help industry meet environmental objectives and there are economic incentives in the UK supporting good practice. The overall impact on CO_2 emissions is a primary concern but also it is important to consider how other gas emissions and resource use levels would be affected. This environmental analysis primarily concerns evaluation of impact on greenhouse gas emissions and water consumption through three main mechanisms:

- 1. Production of high temperature steam using industrial waste heat boilers displaces gas boiler use on site reducing greenhouse gas emissions.
- 2. Production of heat for DH may displace use of gas boilers on the network but may also reduce heat output from the CHP plant. Due to the trade-off between heat and power for an extraction-condensing CHP unit, the heat output reduction means more electricity goes to the grid and marginal electricity generators (usually burning fossil fuels) are displaced from the grid.
- 3. Using a heat pump to supply heat to the network can have the same effects as in mechanism 2 above, but it is necessary to calculate the impact of using electricity to power the heat pump in the overall analysis. Directing waste heat from the cooling system to the DH can also reduce required water abstraction requirements.

To put any emission savings into context, it is necessary to consider the emissions from the steel industry. A case study of Sheffield Forgemasters associated 539 kg CO_2 (eq) life cycle emissions to each tonne of steel ingot produced (Koh et al, 2011), the casting and rolling parts are not considered for the life cycle analysis. In a separate study, rolling and casting were estimated to make up 556 kg CO_2

(eq.) per tonne of steel produced, added to around 642 kg per tonne of steel from the arc furnace (Entec, 2006).

5.5.1 Carbon dioxide emissions analysis

If heat is recovered and used to generate process steam then this displaces use of gas-fired steam boilers. If x units of gas avoid being burned then carbon dioxide saved as given by Equation 5.88. The standard gas boiler is assumed to operate with gross efficiency of 80% and using a fuel of 0.18521 kg CO_2 equivalent per kWh as in Section 3.6.1, bringing total emissions saved to 0.23151 tCO_2 equivalent per MWh of heat used to make steam.

$$CO_2 \text{ saved} = x \text{ MWh} \times 0.23151 \text{ tCO}_2\text{/MWh} \quad (5.88)$$

In this analysis, the carbon footprint for the DH system is calculated relative to a baseline emissions level. The fuel feed rate to the biomass CHP plant's boiler will be unchanged if industry heat was added to the network, and the resulting change is a switch towards less steam extraction from the turbine and therefore more electricity generated for the national grid. Alternatively, the extra heat added to the network may displace gas boilers used in peak demand periods. Hence, overall greenhouse gas emission effects are calculated from changes in gas boilers use and changes in production of electricity for the national grid. Again, it is assumed the gas boilers on the DH system deliver heat with a 80% gross efficiency, as noted in Table 5-8.

The greenhouse gas saving from adding electricity to the grid is properly valued as detailed in Section 3.6.4. For y units of electricity added to the grid, the CO_2 saving is as in Equation 5.89.

$$CO_2 \text{ saved} = y \text{ MWh} \times 0.331 \text{ tCO}_2\text{/MWh} \quad (5.89)$$

Where electricity is taken from the grid to run a heat pump, a grid average emissions factor of 0.449 tCO2/MWh is used. As discussed in Section 3.6.4, emissions from grid electricity may not fall as quickly as projected, so three scenarios are considered in the analysis for possible future emission levels to indicate the effect.

5.5.2 Other emissions

Other closely monitored gas emissions include dioxin species, and while over 90% of human exposure is from dioxins present in food (WHO, 2010), industry is regulated to minimise their dioxin emissions. High temperatures of over 850°C are required to destroy these particles (*ibid.*), and there is a chance of reformation between 500 and 250°C (Born and Granderath, 2013b). Many steelworks use quenching of gases with water spray to pass this critical temperature zone (Born and Granderath, 2013b). Also important issue for heat recovery are flue gas levels of sulphur oxides, if this combines with moisture it creates acid and this can corrode any heat exchanger meaning increased maintenance needs.

5.5.3 Water consumption for cooling

In the UK, industry accounts for 33% of freshwater withdrawals, compared with 57% for domestic use and 10% for agriculture (The World Bank, 2015). Industry may abstract water from ground or surface waters, use it for non-evaporative cooling, and return it to the river after a small temperature rise limited by their environmental permits. The abstraction charges are set by government (Environment Agency, 2014b) but it was found in the study that the financial case for heat recovery would emerge from saving energy rather than reducing abstracted volumes. However, lower abstraction volume requirement will have benefits in securing availability of supplies during times of water shortage.

Benchmark levels of water use are 3m^3 per tonne of product for an electric arc furnace works compared with 5m^3 for an integrated steelworks (Environment Agency, 2004), however Walling and Otts (1967) and World Steel Association (2011) put the figures for an electric steelworks at 14 to 28 m^3. For some processes, the water is limited to a certain temperature rise in the cooling circuits to prevent corrosion, and high water velocities are needed to prevent particles from settling in cooling systems (Walling and Otts, 1967). The adjustment of cooling systems is a complex issue and will require detailed work by engineers to consider consequences before proceeding, however use of high temperature cooling has been achieved in some instances (Schlemmer, 2011). Adjusted cooling could carry environmental benefits in terms of reduced waterabstraction and reduced thermal output to rivers. Not all arc furnace cooling uses river water with some cooling circuits running to cooling towers. Abstraction licence details for the steelworks in Sheffield and Rotherham are listed in Table 5-9.

Table 5-9 : Water abstraction licence details for steelworks in Sheffield and Rotherham.
Source: Environment Agency (2014).

Site	Maximum annual abstraction (m^3)	Maximum daily abstraction (m^3)	Source
Sheffield Forgemasters	6,100,000	26,500	Surface water
Outokumpu Stainless	135,019	421	Ground water
Tata Steel	1,953,000	5,455	Surface water
Tata Steel	6,819,135	36,369	Surface water
TOTAL	**15,007,154**	**68,745**	

Typical energy loss to cooling was discussed in Section 5.3.1. Supposing that water abstracted from a river for non-evaporative cooling purposes leaves the cooling system after a temperature rise of 20°C, each MWh of waste heat would require the abstraction of *x* cubic metres, calculated in equations 5.90 to 5.92 (Coulson and Richardson, 1999).

$$x.c.\Delta T = 1\text{MWh} \tag{5.90}$$

$$x\left(\frac{4.2\ \text{MJ/m}^3\text{K}}{3600\ \text{J/Wh}}\right).20°\text{C} = 1\text{MWh} \tag{5.91}$$

$$x = 42.8\ \text{m}^3 \tag{5.92}$$

where x = volume of cooling water absorbing 1 MWh (m^3);
c = specific heat of water (MWh/m^3°C) from (Coulson and Richardson, 1999); and
ΔT = change in temperature (°C).

Thus each megawatt-hour saved of heat directed towards DH rather than rejected to surface water would save at least 43 cubic metres of abstraction, given a maximum temperature increase of 20°C.

5.6 Economic Analysis

5.6.1 Energy prices

Energy price trends affect profitability of energy intensive industry and the viability of energy efficiency projects including heat recovery. Energy typically makes up 25% of Sheffield Forgemasters' costs (SFIL, 2011). Recent trends in energy prices for UK industry are shown in Figure 5-25.

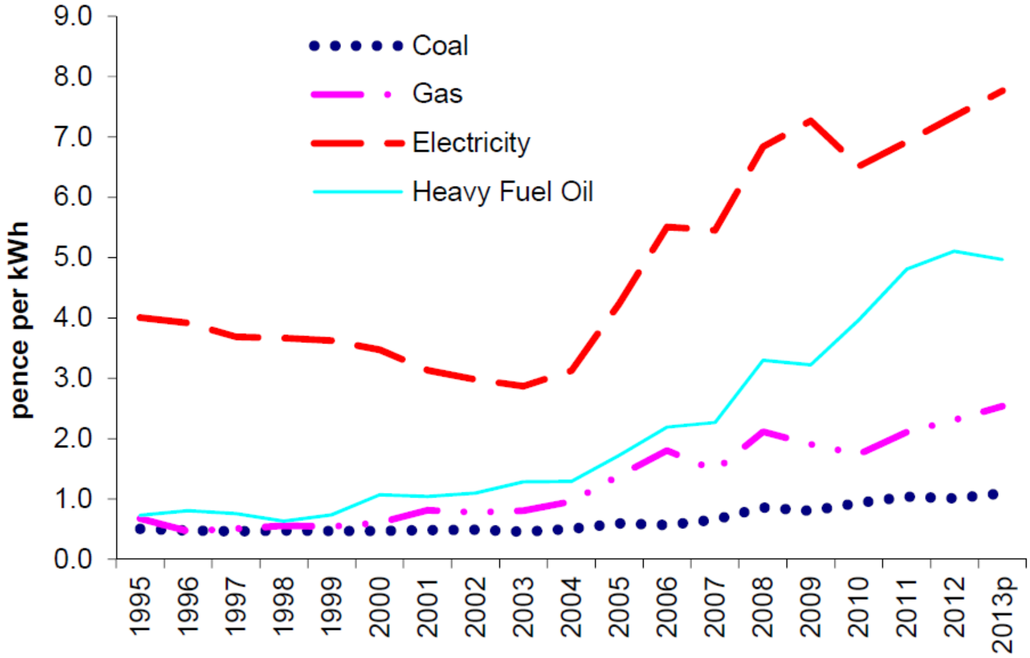

Figure 5-25: Estimated energy prices paid by UK industry from 1995 to 2013.
Source: DECC (2014b).

Future price trends are difficult to predict, but to illustrate present and possible future economic outcomes, the 'high', 'central', and 'low' energy prices projected for by DECC for 2030 (DECC, 2014l) are used in the economic calculation. The economic benefits of heat recovery will depend particularly on the price of natural gas since this is the usual alternative heat source. Since the quantity of biomass supplied to the CHP unit is the same in scenarios with and without heat recovery, variations in the price of biomass for the power plant will not affect the viability of heat recovery.

Energy costs do vary for energy intensive companies from company to company and due to commercial sensitivity concerning energy prices in industry those costs were not made available. Typical energy prices are given in

Table 5-10 from DECC and these include environmental taxes (e.g. CCL) for industry but exclude VAT (DECC, 2014l). The cost of carbon for energy users whose direct emissions are included in the EU ETS are not included in the retail prices, and all prices are expressed in 2014 values in real terms (DECC, 2014l). For the analysis, it is important to note that electricity wholesale costs listed exclude the following contributions: "the costs of transmission, distribution, metering, supplier margins, taxes and the costs of environmental policies where these are charged back to consumers" (DECC, 2014l).

Table 5-10: DECC Energy price projections for 2030, with low, central and high scenarios.
Note: conversion used 1 therm = 29.3 kWh; prices are real and in 2014 terms. Source: DECC (2014l).

	2012 value (p/kWh)	2030 projection (p/kWh)		2030 value as % of 2012 value
Natural gas wholesale price	2.12	Low	1.47	69.6
		Reference	2.61	123
		High	3.68	174
Natural gas industrial retail price	2.49	Low	2.00	80.3
		Reference	3.28	132
		High	4.50	180
Electricity wholesale price	4.82	Low	5.14	107
		Reference	7.28	151
		High	9.28	192
Electricity industrial retail price	7.93	Low	12.5	158
		Reference	13.7	173
		High	15.5	196

In this case study, since the amount of heat sold under the baseline scenario and those with storage and or heat recovery is the same then the cost of heat sale is not needed for the economic calculations. However, if the industry can self-supply some of the captured heat rather than buy in heat from DH then primary energy consumption is changed and the financial benefit to the industry will be enhanced, and in instances there may be opportunities to sell heat to neighbouring industries in a new arrangement or even to supply cooling but these scenarios are not considered in this study.

5.6.2 Electricity market revenue

The wholesale electricity prices quoted in Section 5.6.1 from DECC are broadly representative of the prices paid to generators in the UK; more detail on electricity revenues was given in Section 3.4.2. In order to understand the benefit of altering timing of electricity production, the UK electricity spot market prices for the 12 months running from July 2012 to June 2013 from the ELEXON Portal (ELEXON Portal, 2015) were used in the model matching the period over which heat demands were recorded at the University of Sheffield. This means that any weather-correlation between heat demand and electricity prices were accounted for. As described in Section 5.4.6, the heat storage is deployed to allow the CHP to produce more electricity at higher price periods.

5.6.3 Supporting incentives for CHP

Heat networks will generally link industrial heat recovery plants with CHP plants which are affected by a range of taxes and incentives as well as the electricity market. It was initially considered that recovering heat from industry may compromise some of these incentives and the effects on the incentives are described below. The principal incentive in this case study is the availability of Renewable Obligation Certificates (ROCs), which are provided over 20 years.

Equation 5.93 gives the expression for calculating the Quality Index (QI) where efficiencies are on a gross calorific value basis evaluated over an entire year (CHPQA, 2013b). The coefficients are those for a CHP unit with electrical capacity over 25 MW fuelled with waste wood (CHPQA, 2013b) with further detail given in Section 3.4.4.

$$\mathrm{QI} = 318 \times \eta_e + 120 \times \eta_{th} \tag{5.93}$$

Where η_e = electrical efficiency; η_{th} = thermal efficiency.

The use of heat storage can increase the CHP's heat output by reducing the use of gas boilers for peak demands, and higher heat outputs from the CHP generally boost overall efficiency. It is an important consideration for the heat network that the quality index of the plant is above 100 since heat from a new source (such as industrial waste heat) reduce the heat output from the CHP and may also lead to quality index falling below 100.

Input Calculations

The biomass CHP station will consume 250,000 tonnes of biomass per year (moisture content around 20%) although the plant can operate with high moisture contents such as those found in energy crops and forestry residues of around 60% (E.ON UK, 2014). Assuming this biomass has a net calorific value of 12.5 GJ per tonne (Biomass Energy Centre, 2014) and the gross calorific value is around 6 or 7% higher for wood (Carbon Trust, 2009) with the difference depending on moisture content of the feedstock. Assuming 6% higher GCV, the primary energy input is given by Equation 5.94.

$$\text{Primary Energy Input} = 250{,}000 \times 12.5 \times 1.06 = 3{,}312{,}500\ \text{GJ} = 920{,}000\ \text{MWh/year} \qquad (5.94)$$

Output Calculations

The plant will have an electrical output capacity of 31 MW (Ofgem, 2014) and up to 25 MW of thermal output through the heat network (E.ON UK, 2014) with an electricity-only efficiency of 31.5% (E.ON UK, 2014). Six units of heat are generated by sacrificing each unit of electricity production, as described in Section 5.4.3 (Z-ratio of 6.0, E.ON UK, 2014). The power station will follow the instantaneous heat demand, Q, and have electrical output, P, as in equations 5.95 and 5.96, with gas boilers meeting any shortfall.

$$\text{if } Q<25\text{MW:} \qquad P=31-Q/6.0\ [\text{MW}] \qquad (5.95)$$

$$\text{if } Q>25\ \text{MW:} \qquad P=31-25/6.0\ [\text{MW}] \qquad (5.96)$$

5.6.4 Carbon Price Effects

The carbon price incentives were detailed in Section 3.4.5. EUETS applies for gas boiler use on the DH network and the emissions from gas boilers used on the industry sites. Compensation is given to energy intensive industries due to increased electricity taxes under the EU ETS, for example, Outokumpu's Sheffield site will receive about €1 million compensation annually (Outokumpu, 2014). Sheffield Forgemasters have applied to exclude the Melt Shop and Foundry from the EU ETS under the 'small emitters' opt-out which will allow them a greater number of free allowances if the European Commission approves the UK's plan (SFIL, 2012). The Melt Shop has special protection from the cost of carbon as it is considered to be in a sector with particular risk of 'carbon leakage' where industry might be relocated to outside the EU and result in higher emissions (SFIL, 2012).

5.6.5 Water Abstraction Costs

If the better management of heat on site can lead to lower extraction rates of cooling water then there will be economic savings in the rates the company pays to the Environment Agency. In Yorkshire, there is a standard unit charge of £11.63 per 1000 m^3 of water extracted from the river (Environment Agency, 2014b) however since the cooling circuits are “low-loss” the charges are multiplied by 0.03 and there are also seasonal factors that apply (Environment Agency, 2014b). Changes to these charges were found to have negligible effect on the business case and are neglected.

5.7 Results

5.7.1 Technical and environmental performance

Table 5-11 shows the results from the simulations of various heat recovery options; there are five different heat recovery scenarios and each is simulated with 0, 10 and 20 MWh of heat storage (equivalent to 0, 250 and 500 m^3). The CO_2 emission savings were calculated for each scenario, but since there are savings in scenarios with heat storage but no heat recovery, these had to be distinguished. The CO_2 emission savings attributable to heat recovery were determined by subtracting the equivalent base scenario emissions (from scenario 1, 2, or 3 with the same amount of heat storage but no heat recovery) from the scenario with heat recovery.

The results show there are benefits to the system in terms of reduced gas boiler usage on the network when there is a heat store, even if there is no industrial waste heat recovered (Scenarios 2 and 3). The highest carbon emission saving attributed to heat recovery was 1,521 tonnes of CO_2 equivalent per year, or 25.3 kg CO_2 per tonne of steel produced. With a life-cycle emission level of approximately 539 kg CO_2 equivalent per tonne of steel produced (Koh et al., 2011) this heat recovery would save 4.7% of life cycle emissions including a significant amount of heat replacing gas boiler use for steam production on site. A large reduction of water abstraction arises in the instance that the cooling requirements are met by feeding heat to the DH system, as seen for scenarios 10-15 in Table 5-11.

Table 5-11: Simulation results under various scenarios for energy production and consumption and environmental performance.

Scenario details				Modelled heat production						Environmental outcomes		
Scenario		Industrial waste heat recovered (MWh/a)	Heat store capacity (MWh)	Annual store heat losses (MWh)	Change in CHP heat production (MWh/a)	DH heat from gas boilers (MWh/a)	Heat delivered from heat pump (MWh/a)	Industrial steam generated (MWh/a)	Quality Index, QI	Net change in CO_2 emissions (tCO_2/a)	CO_2 saving attributed to heat recovery (t CO_2/a)	Estimated water abstraction saving (m^3/a)
No	1	0	0	0	0	10,483		0	97.02	0	0	0
Waste	2	0	10	106	1,080	9,509		0	97.09	-166	0	0
Heat	3	0	20	212	1,829	8,865		0	97.15	-274	0	0
EAF	4	7,525	0	0	-4,616	9,643		2,000	96.68	-912	-1,060	0
Flue	5	7,525	10	106	-3,618	8,692		2,000	96.75	-1077	-1,063	0
	6	7,525	20	213	-2,884	8,074		2,000	96.81	-1180	-1,058	0
Gas	7	4,000	0	0	-3,158	9,652		0	96.79	-367	-472	0
Furnace	8	4,000	10	106	-2,140	8,732		0	96.86	-523	-465	0
Flues	9	4,000	20	212	-1,438	8,134		0	96.91	-623	-459	0
EAF	10	4,215	0	0	-4,428	9,656	5,255	0	96.69	36	-20	179,942
Cooling	11	4,215	10	106	-3,399	8,723	5,270	0	96.77	-122	-14	180,445
Heat Pump	12	4,215	20	212	-2,676	8,104	5,270	0	96.82	-225	-11	180,445
All	13	13,740	0	0	-11,436	8,367	4,106	2,000	96.18	-1215	-1,521	140,600
Three	14	13,740	10	107	-11,016	7,489	4,602	2,000	96.21	-1351	-1,505	157,582
Options	15	13,740	20	216	-10,610	7,033	4,770	2,000	96.24	-1419	-1,475	163,331

The use of gas boilers for district heating cannot be completely eliminated because there will be periods of planned and unplanned outage when the CHP is unavailable. In addition to this, in winter there is limited opportunity to charge the store overnight when demand is low but not sufficiently low below the CHP's maximum heat output to allow sufficient charging. Heat storage increases the utilisation of the heat from the CHP unit, boosting the incentives per MWh of electricity produced (as discussed in Section 5.6.2) and also reducing the use of more expensive gas boilers, therefore providing economic as well as environmental advantages. The incremental benefits of heat storage in terms of reduced use of expensive gas boilers, for the network fall as the heat store capacity rises, is shown in Figure 5-26.

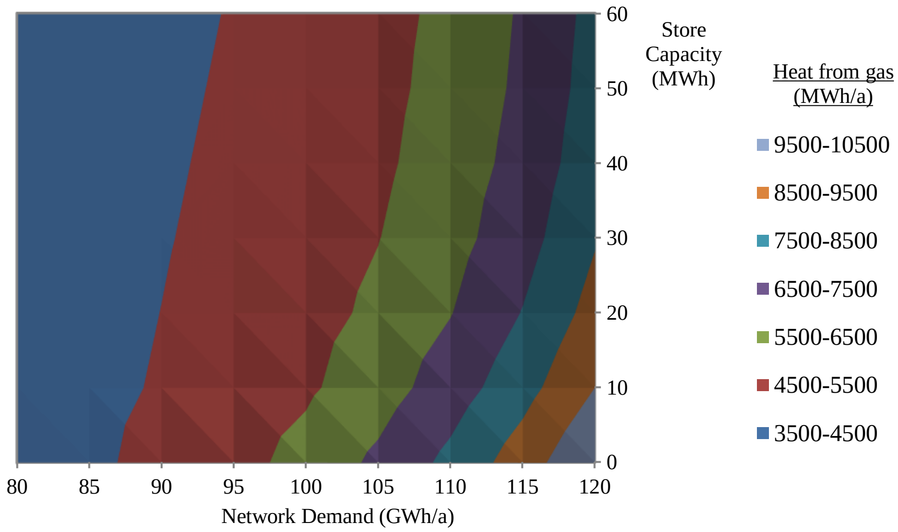

Figure 5-26: Simulation results showing the reduction in gas boiler use for the heat network without industrial heat recovery, with various network demand levels, and with various heat store capacities.

In future years the environmental outcomes will change, particularly in response to projected change in the CO_2 emissions associated with UK grid electricity, as discussed in Section 5.5.1. Figure 5-27 shows the expected CO_2 emission savings along with those seen under scenarios of reduced CO_2 emissions associated with grid electricity. The biggest CO_2 savings are seen in scenarios 4, 5 and 6 where captured heat is displacing the use of gas-fuelled steam boilers (for steam generation) on site. Where heat is used just to generate heat for DH and not for steam processes, the environmental advantages are less for example in scenarios 7, 8, and 9 where heat from the gas furnaces are used to provide heat for DH but not steam.

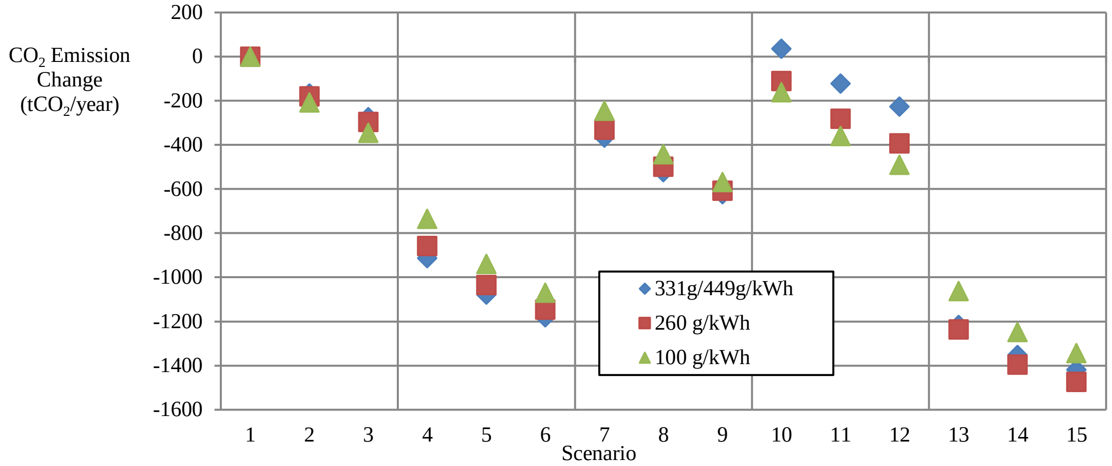

Figure 5-27: The carbon dioxide emission savings under current circumstances (331g/kWh for CHP exporting and 449g/kWh grid average) and two scenarios for reduced carbon emission intensity of grid electricity.

The environmental advantages of using cooling water as a heat source are low, as seen in scenarios 10-12. The decarbonisation of electricity from the grid increases the benefits of using heat pump technology but reduces the carbon emission benefits of the other heat recovery options since extra electricity from the biomass CHP going to the grid gives less benefit as the grid average carbon intensity falls. In scenarios 1, 2 and 3, displacing gas boiler use through using more heat from the CHP in combination with heat storage and therefore reducing the CHP's electrical output has greater benefits when extra electricity supplied to the grid to make up for this has lower carbon intensity.

Figure 5-28 shows the CO_2 emission benefit beyond that seen in scenarios without industrial heat recovery. Figure 5-29 and Figure 5-30 show the load duration curves in scenarios 4 and 6 with industrial heat recovery and respectively 0 and 20 MWh of heat store capacity. The figures show how biomass CHP and gas boiler heat sources meet heat demand. The main effect of the heat storage is to shift timing of heat outputs so there is maximum heat output at times of low electricity prices and vice versa, and also to reduce the amount of gas used while the CHP unit is running at its maximum heat output of 25 MW by increasing the heat output of the CHP at other times.

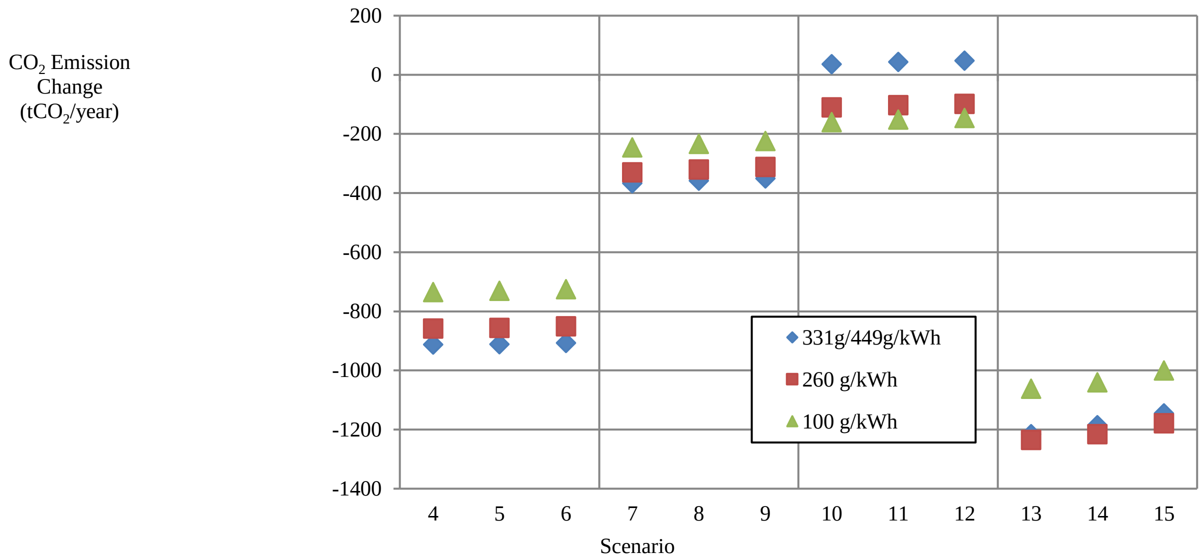

Figure 5-28: The carbon dioxide emissions savings attributable to the heat recovery, as opposed to the use of heat storage. Note: Scenarios 1, 2 and 3 (not shown) have zero change and act as the base scenarios without heat recovery (120 GWh/a).

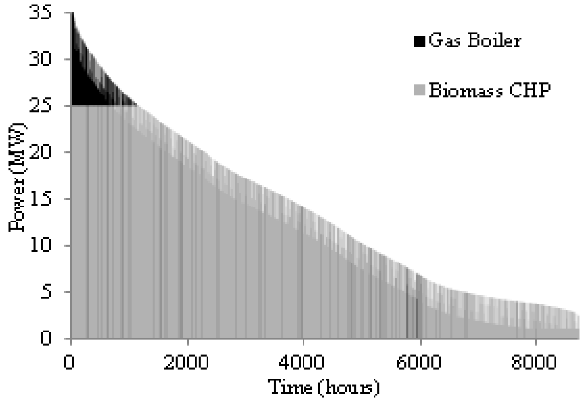

Figure 5-29: The load-duration curve with industrial heat recovery but no heat storage, Scenario 4.

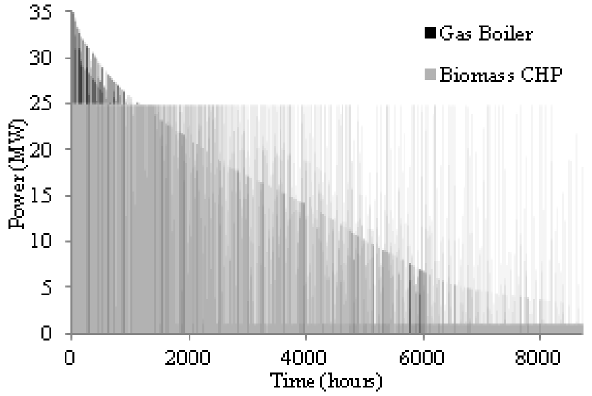

Figure 5-30: The load-duration curve with industrial heat recovery, 20 MWh of heat storage, CHP timing optimised, Scenario 6.

The peak half-hour average demand for heat over the year is modelled to be 37.5 MW in this instance; since this heat demand is present for only one half hour period it does not show clearly on the load-duration curves. The algorithm for heat storage control did not use the heat storage to reduce the capacity of peaking gas boilers required, but this could have been an additional advantage.

In summer, the demand for heat is low meaning waste heat production from the steelworks can be a similar size to the heat network demand. Some heat will be lost if heat storage is not used, but this was only found to be a very small amount in the case of this single steelworks connecting to the network. Also, if the temperature of the waste heat is too low to add to the network but it is to be used elsewhere on the SFIL site then storage of the heat over a multi-day time period will be important to maximise the recycling of heat on site. There may be other industrial sites nearby and a coordinated approach to heat injection could be beneficial.

5.7.2 Economic Performance

There are economic advantages found for introducing heat storage with the model; these advantages are shown in Figure 5-31. The ROC revenue falls mainly as a result of lower electricity production but it is worth noting that for the case study, the ROC support will end in June 2034 as these subsidies have a limited lifetime of 20 years. Figure 5-32 shows how the overall economic performance varies with demand level and store capacity. For the lower demand instances there is greater benefit from moving electricity production around and less benefit from reducing gas consumption, however the overall profit is quite consistent over different demand values. Abstraction charges were also calculated using guidance from the Environment Agency (Environment Agency, 2014b) and the overall saving from reduced abstraction in scenarios 10-15 was calculated as less than £100 and therefore has been omitted from the final analysis.

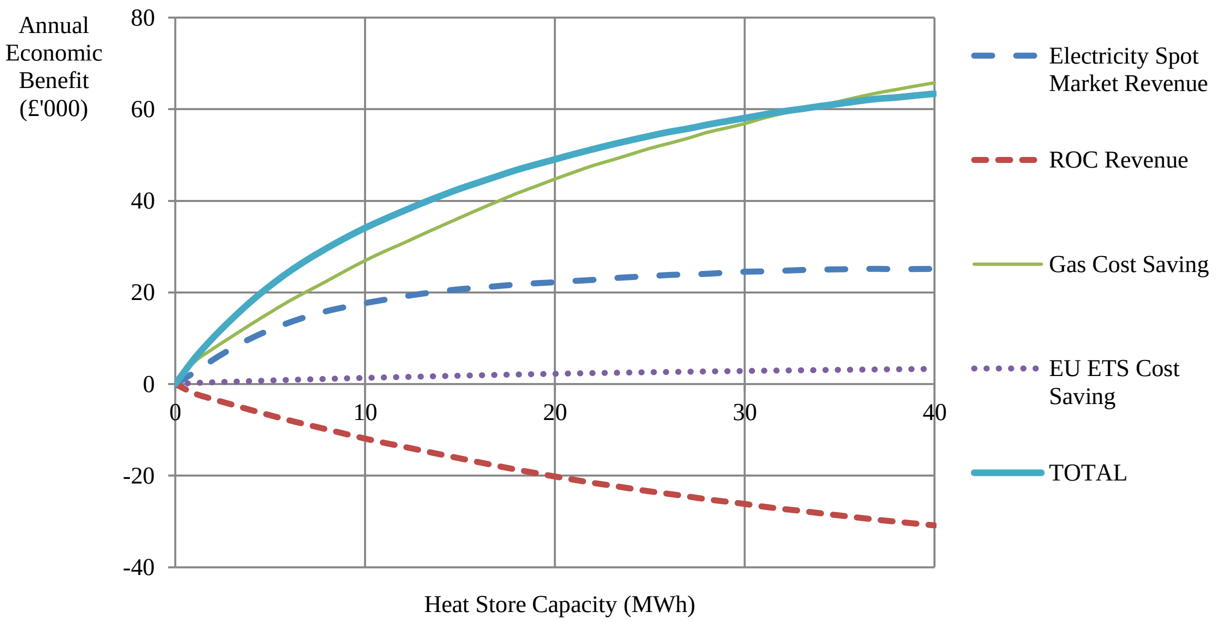

Figure 5-31: The economic effects concerning revenues of adding heat storage to the system without industrial heat recovery. Note: Annual demand =120 GWh/a.

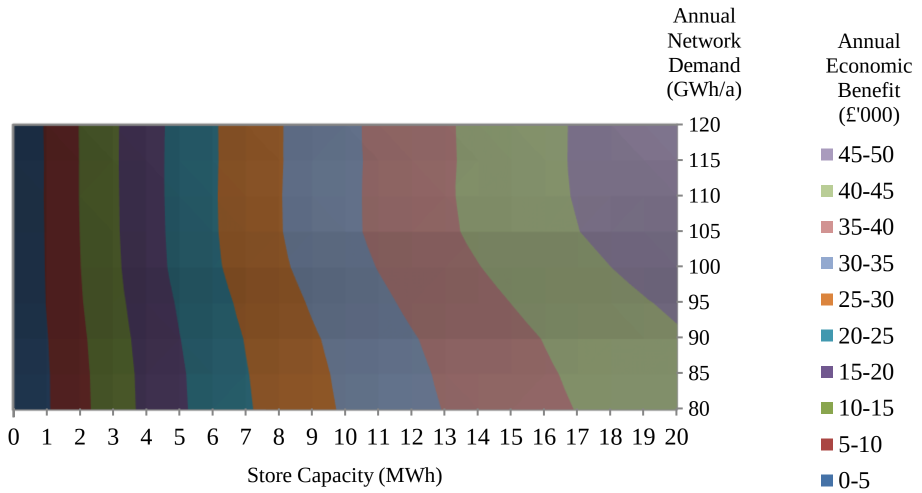

Figure 5-32: The economic benefit (net revenue) according to store capacity and network demand.

Figure 5-33 shows the results of the economic analysis across the different scenarios using the assumptions detailed in Table 5-8. Industry cost saving is from reduced need for gas boilers to generate steam for use on site. The DH operator net revenue change is made up of altered electricity revenues and savings from reduced use of natural gas boilers for supplementary heat for the network. These revenues would have to be sufficient to justify the capital investment in the project, any resulting operational and maintenance costs, and any other project costs.

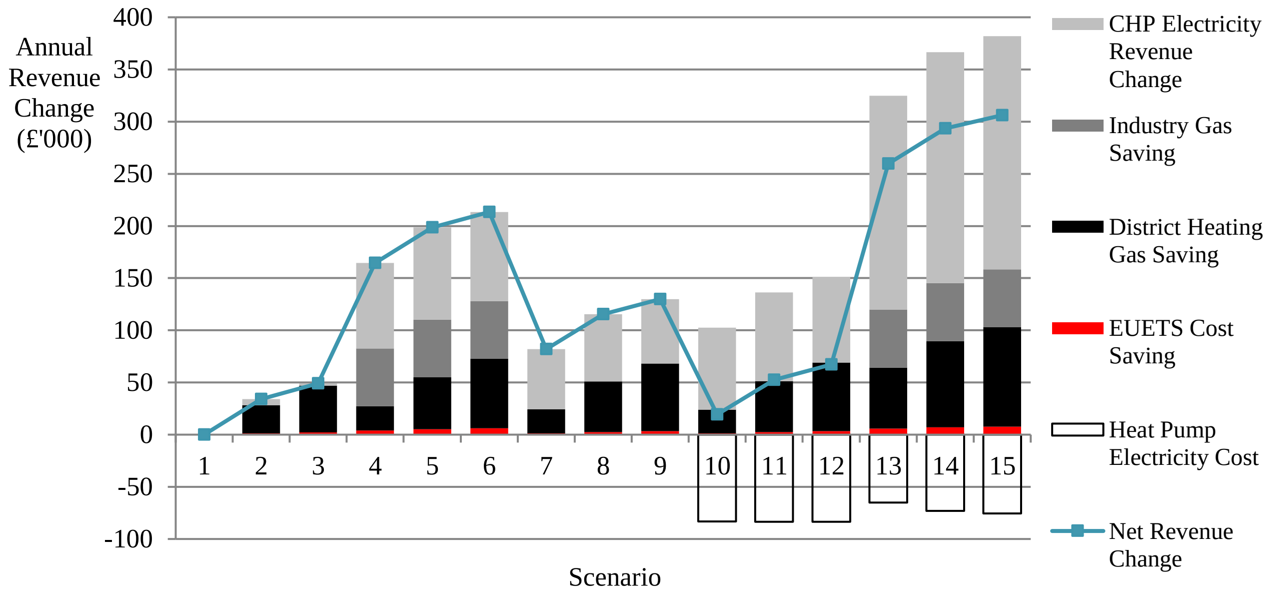

Figure 5-33: Annual revenue changes for each scenario.

The Quality Index (QI) has been calculated for each scenario and the values were all below 100 as shown in Table 5-11. The threshold for heat demand such that QI of 100, the importance for which was explained in Section 5.6.3, is actually achieved is around 210 GWh per year for this CHP unit as shown in Figure 5-34 showing QI values from model runs with higher annual heat demands. The figure shows how the threshold of demand to reach QI=100 is higher for cases with industrial heat recovery, in that case 13.9 GWh/year of heat from industry are delivered to DH as in Scenarios 12 to 14.

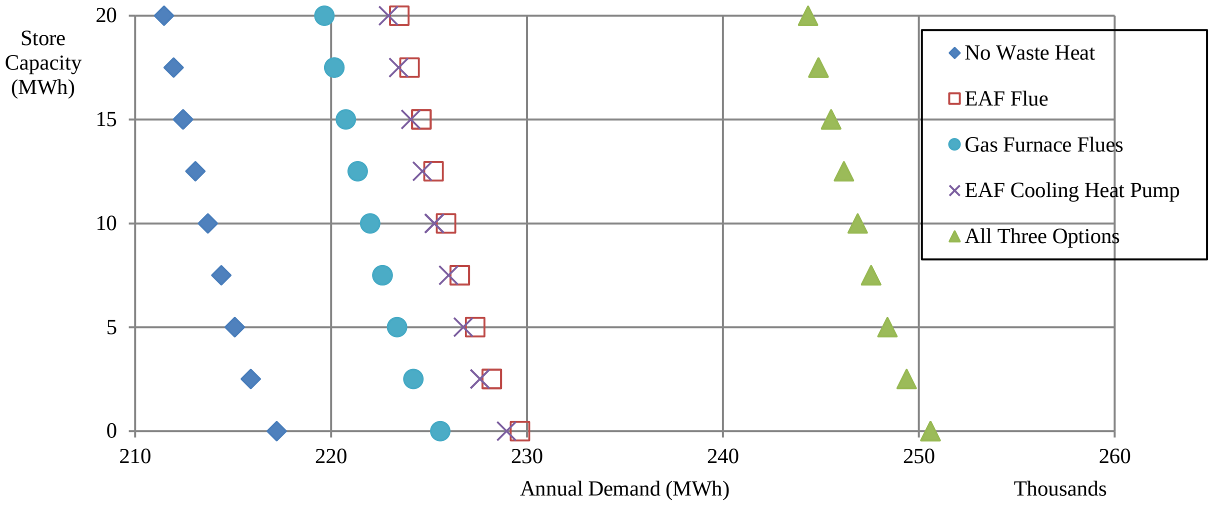

Figure 5-34: Location of QI=100 threshold in different heat recovery and storage scenarios.

Figure 5-35 shows the projections for how the net revenues would be different in 2020 and 2030 based on the UK Department of Energy and Climate Change price projections (DECC, 2014l). These projections include central, high and low price scenarios for gas and electricity, shown respectively as a cross and the upper and lower error bars. These projections naturally have high levels of uncertainty but the scenarios give some guidance as to what the revenues could be in future.

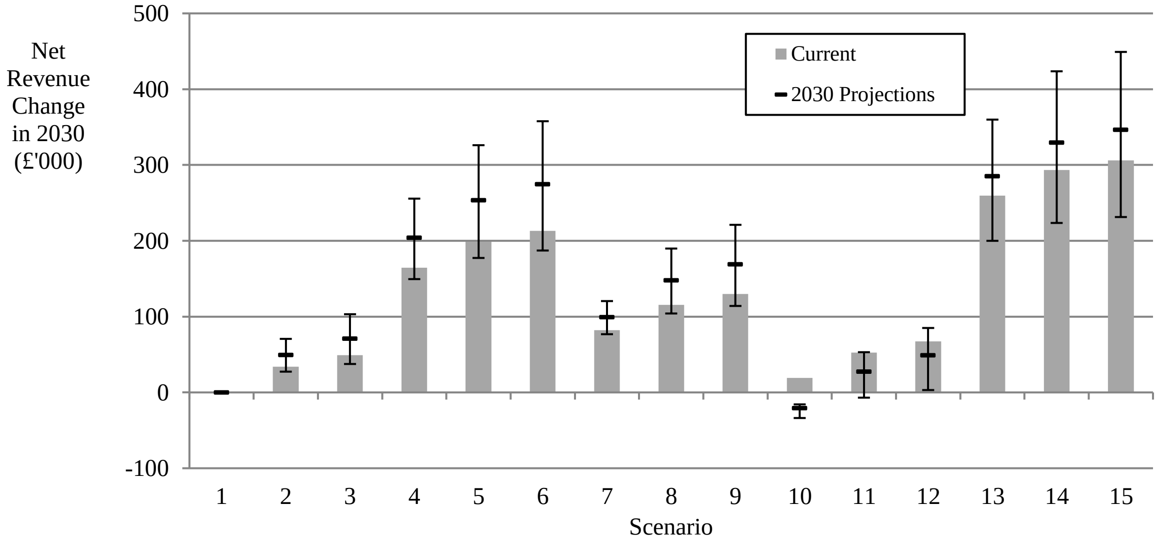

Figure 5-35: The annual revenues under current circumstances and in 2030 with 120 GWh/a under high, low and central scenarios for energy price changes from (DECC, 2014l).

The high price scenarios generally mean increased revenues for heat recovery; there are two exceptions among the scenarios in scenarios 10 and 11 where high electricity prices result in a worse (and possibly negative) overall revenue by 2030 for the case of a heat pump driven by electricity. The results show that direct recovery of heat from the flue ducts gives high and positive economic return under the scenarios tested.

5.8 Discussion

5.8.1 Network resilience, bottlenecks, smooth supply

Flow limitations near the periphery of the heat network where smaller pipes are laid make some locations impractical for large heat storage installations. The best location for heat storage in this case study is likely to be at the industry site where supply variations from intermittent production of heat can be isolated from the wider network. Smooth supply of heat to the network helps avoid ‘water hammer’ effects (Coulson and Richardson, 1999) where pressure shocks from flow changes can cause damage to the network. Also, the heat network pipes should not be allowed to cool significantly from their operational temperatures as thermal expansion and contraction reduce the lifetime of the pipes. Continuity of a small amount of flow along the main arteries of the network needs to be maintained and this was an implicit assumption used in the modelling, manifesting as a minimum supply of heat from the CHP plant along the network artery.

With a heat recovery project, smaller pipes leading to the heat source will reduce the capital cost significantly, but will also limit the rate at which heat can be fed to the network (avoiding hydraulic shocks). In the current case study, the main heat source is only a matter of metres from the main spine of the new heat network, but this issue may be more relevant if other waste heat sources in the city wish to join the networks.

5.8.2 Alternative carbon emission reduction strategies

The carbon emission savings seen in section 5.7.1 should be compared with those likely to arise from the decarbonisation of UK grid electricity due to the changing mix of power generation. The high use of electricity in the electric furnace would mean falling overall emissions from this industry site, and the carbon dioxide reduction figures given in Table 5-12 assume electricity consumption of 600 kWh per tonne of steel produced. By 2030, the overall CO_2 reduction could be 10,000-16,000 t CO_2/year in this ‘business as usual’ scenario and the benefits from heat recovery are in addition to these savings. For context, a baseline figure of 539 kg CO_2 (eq.)/tonne of steel life cycle emissions (Koh et al., 2011) means current emissions of 32,400 t CO_2 (eq.) per year. CO_2 factors for grid electricity varies widely according to the country as shown in Table 5-13.

Table 5-12: Reductions in base case carbon dioxide emissions associated with decarbonisation of the grid.

Electricity consumption in arc furnace	Grid CO_2 intensity (g/kWh)	Annual production of steel (t/year)	CO_2 emissions for consumed electricity (t CO_2 (eq.)/year)	CO_2 reduction (t CO_2 (eq.) /year)
Assuming 600kWh/tonne	537	60,200	19,396	-
	260	60,200	9,391	10,005
	100	60,200	3,612	15,784

Table 5-13: Carbon intensity of grid electricity by country.
Source: Brander et al. (2011).

Carbon intensity of grid electricity (kg CO_2(eq.)/kWh)			
Austria	0.177	Italy	0.411
China	0.975	Sweden	0.023
France	0.071	UK	0.509
Germany	0.672	US	0.547

An additional carbon saving could be achieved by the use of scrap metal preheating; redesign of the arc furnace flue extraction system to capture heat gives rise to this possibility. Scrap metal preheating could save as much as 100 kWh of energy consumption per tonne of steel produced (European Commission, 2013). This electricity saving is translated into CO_2 equivalent and projected cost savings for 2030 in Table 5-14. It is sensible to work with a conservative estimate as there are problems in using scrap preheat in these batch furnace processes compared to some furnaces that run more continuously. However, if 50 kWh per tonne of steel could be saved through scrap preheating, this would equate to 3000 MWh of electricity saved per year and a further CO_2 reduction of 1351 tonnes equivalent per year.

Table 5-14: CO_2 emission saving estimates for scrap preheating and 2030 projections for electricity cost saving.

Electricity consumption reduction from scrap preheating	Grid CO_2 intensity	Annual production of steel (t/year)	CO_2 reduction (t CO_2 (eq.) /year)	2030 electricity cost saving (£'000/year) (high/ref/low)
Assuming 100kWh/tonne	at 449 g/kWh	60,200	2,703 t CO_2 (eq.)	933/825/753
	at 260 g/kWh	60,200	1,565 t CO_2 (eq.)	933/825/753
	at 100 g/kWh	60,200	602 t CO_2 (eq.)	933/825/753

The substitution of carbon-intensive feedstocks for industrial processes is another option but with lower impact for the electricity-intensive arc furnace method; biomass-derived alternatives such as charcoal and biomass gasification syngas is the focus of a European project called GreenEAF (European Commission, 2013b). The use of 'green gas' on site could reduce emissions but there are also many other uses for it across the economy. Carbon Capture and Storage or Utilisation is not expected to be viable for EAFs due to low CO_2 concentrations in the flue gases. The prospects for industrial carbon capture and storage at the blast furnace sites, including in the Humber region, are more promising in this respect.

The alteration of emission savings under an optimistic (100g/kWh) and pessimistic (260g/kWh) grid decarbonisation scenario were shown in Figure 5-27. The carbon dioxide savings from implementing heat recovery will be lower, but are likely to make up a similar proportion of the life-cycle emissions in 2030.

5.8.3 Waste heat volumes, store capacity and seasonal heat storage

Since the volumes of industrial waste heat recovered are small compared to the total heat load on the network, the computer algorithm described the system as working well without any heat storage linked to the heat network. There is still a steam accumulator that is balancing high temperature waste heat as steam, and it will be the high temperature heat recovery that is most variable for the intermittently used arc furnace flue. However, the conclusion of zero storage working well may be unrealistic in practice because variability of heat production from industry is not accurately described at the half-hour intervals at which the energy system is modelled. A small buffer, that can smooth out the variability in heat production shown in Figure 5-12 and Figure 5-14, is likely to be essential but since there are short-term fluctuations a heat store of around 100 m^3 (4 MWh) would be sufficient to prevent hydraulic shocks damaging the network, and as such can also provide wider benefits to the DH operation as shown in Figure 5-31 which concerns the benefit of a store serving DH only.

In the model, the store was only required to manage small mismatches between supply and demand of a few megawatts over a period of a few hours, reflecting the low amount of waste heat compared to the annual heat demand. However, if two or three of the steelworks are connected there may be too much waste heat in summer creating need for long-term seasonal heat storage. This issue will be explored further in Chapter 6 which will look at larger scale heat network use in Sheffield and the prospects for multiple waste heat inputs.

5.8.4 District heating operating temperatures and cooling water heat recovery

Lowering the DH operating temperature would mean that heat is more readily absorbed through heat exchangers or more efficiently supplied by heat pumps. If the DH temperature is low enough, an arc furnace could operate with a high temperature cooling system in order to deliver heat at the right temperatures. This would allow recovery of the cooling water heat without the economic and environmental penalties that were evident in the heat pump scenario results of Section 5.7. It has been assumed here that the heat pump can deliver heat into the network just like any other heat source, but since the network temperature is higher than available heat pumps can deliver, then raising the temperature of output from the CHP may be necessary or using a gas boiler to add energy may be necessary to compensate for this. This factor simply reinforces the findings, since the use of a heat pump was found to be the least environmentally and economically feasible option for feeding heat to DH. Lower operating temperatures could also make it easier in future to add heat sources such as solar thermal and geothermal energy.

5.8.5 Financial Issues

In future, the level of steel production may increase or decrease and this needs to be considered when looking at the investment case. Risk plays an important role in the determination of financing costs for a heat recovery project. Uncertainty over the future costs of energy and carbon emissions, as described in Sections 5.6.1, are significant concerns for industry (Ricardo-AEA, 2013). Element Energy (2014) found that UK industry is unlikely to invest in projects that have a payback period of more than two years so this may significantly limit opportunities. Longer payback periods are acceptable in the energy industry; the district heating sector is familiar with investment periods of 15, 20 or even 30 years (Frederiksen and Werner, 2013). The estimated annual economic benefits were considered, and it appeared that heat recovery projects would pay back over several years. The price for any heat sold into the district heating network would naturally be subject to negotiation as would the operating practice for the thermal store. The outline business case seems for preheating of scrap seems promising based on figures calculated in Table 5-14 based on a saving of 100 kWh per tonne of liquid steel, but site-specific practical issues may prevent adoption.

5.8.6 Social Issues

There are a complex range of stakeholders involved in such a project. There are the operators of the district heating network who, from a simple economic perspective, seek to maximise revenue from heat and power sales while minimising costs. Reducing carbon emissions and ensuring the sustainable use of biomass may be considered as secondary to this however increasingly the sustainability of business models and the responses to environmental challenges are important to the customers as well as to policy-makers who can influence industry behaviour through incentives or taxes.

The heat network customers are also crucial stakeholders that require assurance of the resilience, cost and sustainability of their energy supplies. Upham and Jones (2012) found that industrial waste heat was viewed most positively amongst the potential heat sources by UK customers. There may be resistance in this instance due to the introduction of non-renewable heat to a heat network that could be using the renewable nature of the heat as a selling point. At the moment there is little regulation of heat networks in the UK as the industry is relatively small, a new initiative called Heat Trust was established in November 2015 to develop customer service standards (Heat Trust, 2016). The current lack of official regulation does however makes it difficult to reassure potential heat customers (DECC, 2013n).

5.9 Conclusions

This work has developed a new methodology to evaluate the different options for integrating industrial heat recovery to a DH system, finding the economic and environmental benefits while considering issues of system control. A central part of this work was to provide insight on the role of heat storage in this process and to demonstrate the benefits of storage to the heat network in a wider perspective than just the heat recovery process.

- **Research into the industrial systems at an Electric Arc Furnace steelmaking site allowed the most promising waste heat sources to be identified.** This was a process undertaken through a literature review, a site visit and consultation with Sheffield Forgemasters International Ltd, and by calculations to provide further evidence.
- **The most promising strategy for heat recovery was to target high-temperature waste gas streams in order to generate steam for re-use on site and DH water.** If scrap metal preheating and improved off-gas control were incorporated this could increase benefits but the merits of each addition would need to be weighed against the extra costs. Recovery of waste heat from EAF flue gases allows reduced gas consumption for generation of steam and excess heat can contribute to DH, saving 912 tonnes of CO_2(eq.) per year.
- **Heat recovery using a heat pump would not offer significant economic or environmental benefits even though the energy lost to cooling water is significant.** The conversion of cooling systems to operate at high temperatures could be an effective means to capture this waste heat stream and pass the energy to DH, providing similar benefits as heat recovery from the gas furnaces. Even if the UK grid electricity undergoes significant lowering of carbon footprint then there appears to be little benefit in terms of overall carbon dioxide emissions

from using a heat pump to recover the lower grades of waste heat. However, reduced abstraction of river water for cooling could provide benefits to wildlife and reduce stresses on the water system during periods of drought.

- **Industrial waste heat from the case study site could provide up to approximately 14,000 MWh per year for DH and save the use of 2200 MWh of gas used to generate steam for industrial processes**. This quantity of DH energy is greater than 10% of the energy provided through the city-centre DH networks.
- **The benefits of using recovered heat energy for electricity generation were judged to be lower after a review of organic Rankine cycles and steam cycles for electricity generation.** Intermittency of the processes is problematic in order to size either an electricity generation apparatus, but equally the intermittent use of a large heat pump for recovering energy from lower temperature heat sources should be avoided for the best economic results.
- **Introducing heat storage of various quantities to the energy system model provided benefits to the DH system.** Only a small quantity of heat storage at the steelworks would be required to manage intermittency of heat production and prevent hydraulic shocks in the network. Larger stores provide benefits to the CHP unit allowing greater production of electricity at peak price periods, but the incremental benefits fall as the store volume increases and therefore there will be a most cost-effective size for the store. Since the volume of waste heat production was small compared to annual demand, inter-seasonal heat stores were not required.

5.10 Summary

Some energy use data from SFIL was combined with energy use estimates based on research into steelmaking processes found in published research. From this, estimates of energy inputs and losses as waste heat were produced to inform the energy system modelling. Values for technically recoverable heat were developed based upon estimated annual production figures that were in the public domain and these were combined with estimates for energy consumption per unit produced along with how much heat could be recovered from different waste heat streams.

A computer algorithm was developed in order to study the heat recovery and DH system. The operational dynamics were informed through discussions with E.On and Veolia who operate Sheffield's district heating (DH) schemes as well as from references in the literature. The flexibility of the model allowed the author to investigate different system variables, to make use of heat demand data from the University of Sheffield as a realistic demand profile, and to simulate the benefits of a heat store to the heat recovery process as well as to the DH system.

Different heat stores were added to the network in the models enabling the economic and environmental outcomes to be quantified and analysed. The most promising methods of heat recovery were found, and the model will be applicable to other circumstances of heat recovery in Sheffield and in other UK locations.

6 HEAT STORAGE FOR SHEFFIELD'S DISTRICT HEATING NETWORK

6.1 Introduction

6.1.1 The City Centre District Heating Network

Sheffield's city centre district heating (DH) network is one of the largest in the UK and is shown on the map in Figure 6-2. It has a total pipework length of over 50 kilometres, connects to over 150 buildings, and operates without a heat storage buffer vessel. Figure 6-2 indicates the locations of the buildings on the existing network, and Figure 6-1 shows the breakdown of heat demand according to building function.

The internal diameters of the network's insulated pipes are up to 400mm with outer diameter 520mm near the heat source (Vital Energi, 2014) with pipe diameters getting smaller towards the periphery of the network. The network has control systems based on Programmable Logic Controllers to ensure that temperature and pressure readings are continuously fed back to the heat source (Mildenstein, 2004).

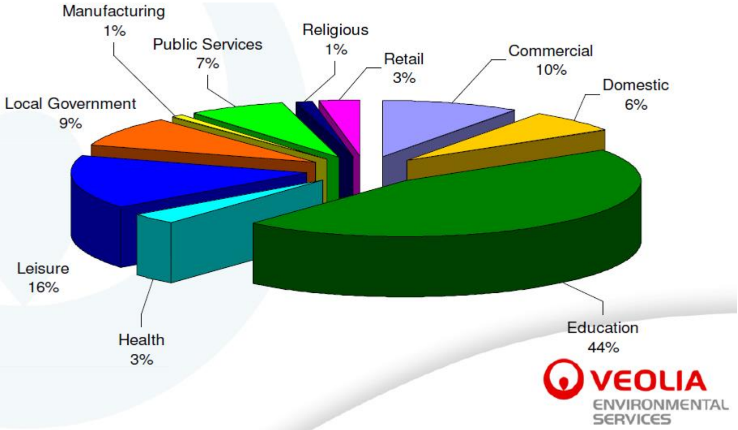

Figure 6-1: The diversity of heat load types on the Sheffield DH network.
Source: Veolia Environmental Services (2010).

On winter mornings, the thermal energy in the DH system is increased in advance of the demand peak by raising the temperature of the supply water by a few degrees (Veolia Environmental Services, 2013b); hence the pipes themselves offer some storage capacity over short timescales. The network operator has been considering the use of a buffer tank for heat storage for smoothing peaks since at least 2008 (E.ON, 2008).

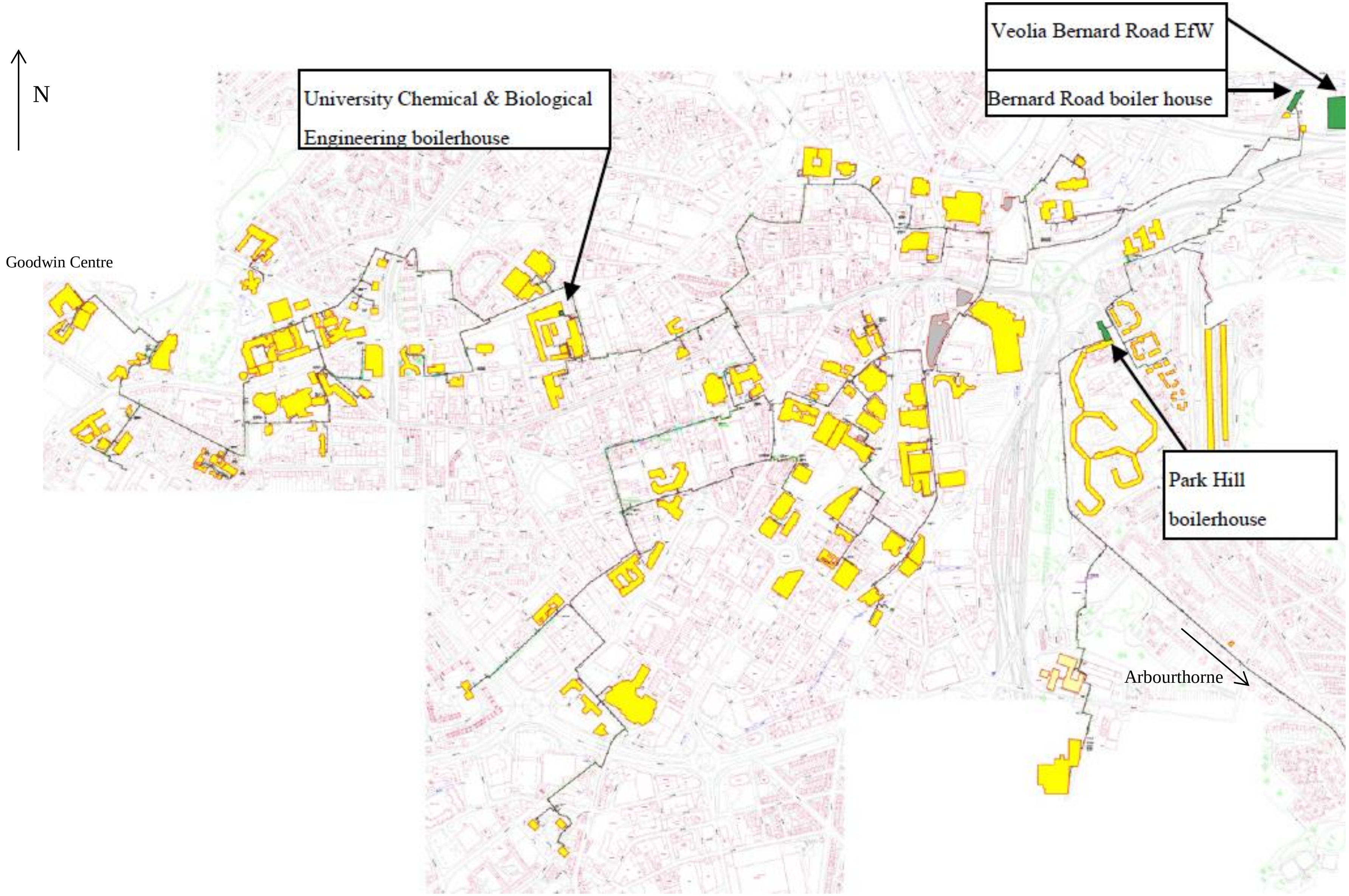

Figure 6-2: Sheffield Heat Network layout.
Source: ARUP (2012).

Supply temperatures in the city centre network are around 110°C; this supply temperature is relatively high compared with DH schemes in Sweden (Frederiken and Werner, 2013). With conventional radiators the supply temperature could work at a little over 85°C, but the high temperature of the supply water allows for heat to be carried in a smaller volume and hence the size of pipes required were smaller and more economical to lay at the time (Mildenstein, 2013).

6.1.2 District Heating Energy Centres

The Sheffield Energy Recovery Facility (ERF) energy centre provides low cost heat through the network, fuelled by municipal solid waste processed at the plant all year round. The incineration process can produce up to 39 MW of thermal output for DH and up to 17.5 MW electrical output for the national grid (Environment Agency, 2007). The balance between heat and power outputs can be adjusted depending on the heat demand and will be explored further in section 6.2. Around 20,000 MWh of the annual electrical output from the steam turbine is used on site (Kirkman et al, 2010).

In 2012, the ERF produced 95,559 MWh of electricity, more than twice as much electricity as any other UK DH scheme, and 108,000 MWh of heat (DECC, 2014n). The net calorific value for waste fuelling the plant is 2.6 MWh/tonne (9.36 MJ/kg, Kirkman et al., 2010). The boiler houses on the network, highlighted in Figure 6-2, contain back-up boilers as well as electrical pumps to maintain pressure to the furthest points in the system.

The ERF is near capacity in terms of heat connections currently and the DH operator does not have major plans to expand (WYG Engineering, 2010). The feasibility of additional customers is affected by the shape of the network and the local pipeline diameters (*ibid.*) and the availability of additional heat sources.

The new Blackburn Meadows biomass CHP development, featured in detail in Chapter 5, has its own DH network just a few kilometres northeast of the city-centre network. Interconnection of the systems may prove one way to increase the thermal capacity of heat sources present and relieve current constraints on the scope for expansion of the city centre network. The interconnection option will be explored in this chapter.

6.2 Operation Analysis

The incorporation of heat storage could improve the system's environmental and economic performance, hence quantifying performance criteria will assist in evaluating outcomes.

6.2.1 Carbon Emissions Factors

The provision of heat to Sheffield's DH prevents in the region of 21,000 tonnes of CO_2 emissions that would occur by the use of gas boilers (Veolia Environmental Services, 2013). This figure is broadly consistent with a heat supply of 100,000 MWh per year with a gas boiler emissions factor of 0.23 tonnes CO_2/MWh.

In the full analysis, electricity supplied to grid receives carbon credits for displacing electricity production from the marginal power station on the network which is likely to be a coal or gas-fired power station. At its design throughput of 225,000 tonnes of waste per year the emissions from landfill are said to be reduced by up to 116,000 tonnes of CO_2 equivalent whilst the actual direct emissions from the facility itself are of the order 88,000 tonnes (Kirkman et al., 2010).

For the year to the end of May 2012, the emissions factor per kWh of heat supplied through the network was calculated as 0.132 kg CO_2 /kWh (Veolia Environmental Services, 2012) which determines the off-takers' liability for the Carbon Reduction Commitment (CRC) (ARUP, 2012).

ERF Plant Availability

Figure 6-3 shows monthly availability and carbon emission factors for the Sheffield ERF and the city centre DH network. When the plant is unavailable then the emissions factors for heat production rise significantly since back-up boilers using gas or oil are required to provide additional heat.

Veolia Environmental Services (2010) reported that oil and gas heat contribute 18% of the district heat production, while in 2006 this was estimated as 15% (IT Power, 2006). Some gas is needed to restart the combustion process after shut-down periods while some is needed for top-up heat.

The data contained in Figure 6-3 was converted to numerical values for analysis using digitising software created by (Rohatgi, 2013). The data is shown in Figure 6-4 with the number of operational hours converted into an availability percentage figure by dividing by the number of hours in each month.

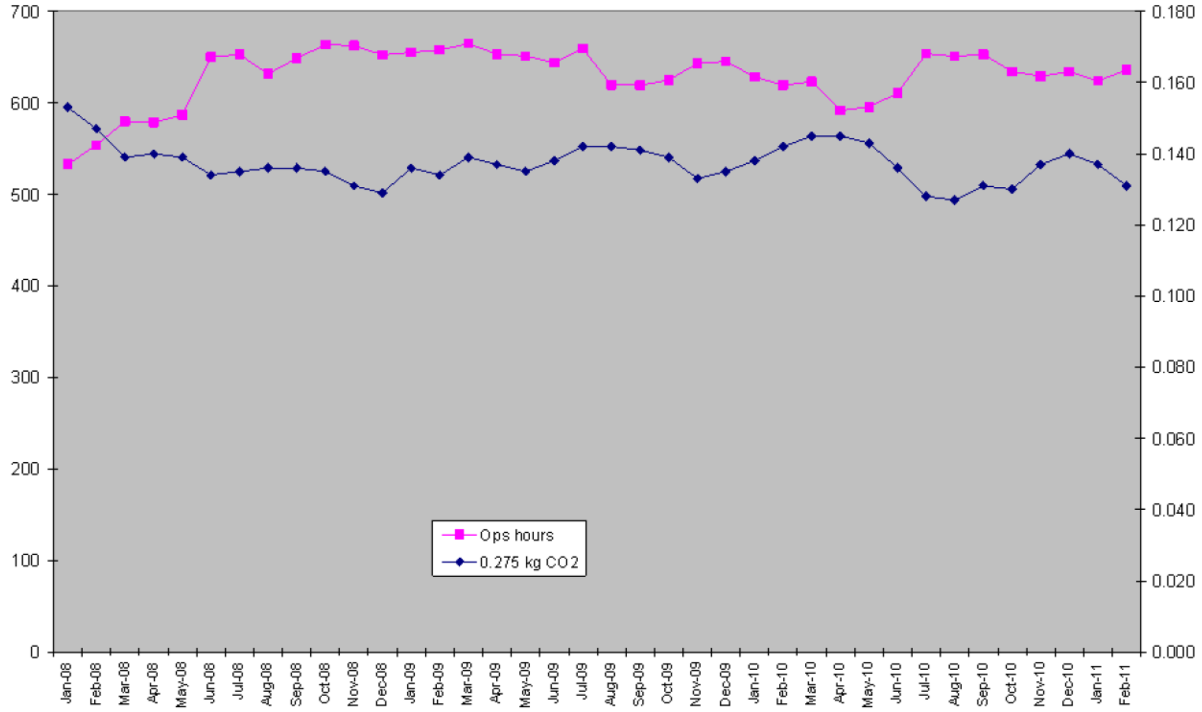

Figure 6-3: Figures showing the monthly operating hours and emissions factors.
Source: ARUP (2012), information courtesy of Veolia Environmental Services.

Regional degree day data was available for the time period in question from Degree Days Direct Ltd. (2013) and this data was applied to each month to investigate weather-correlation of the emissions factor. The degree-day analysis resulted in a correlation shown in Figure 6-5.

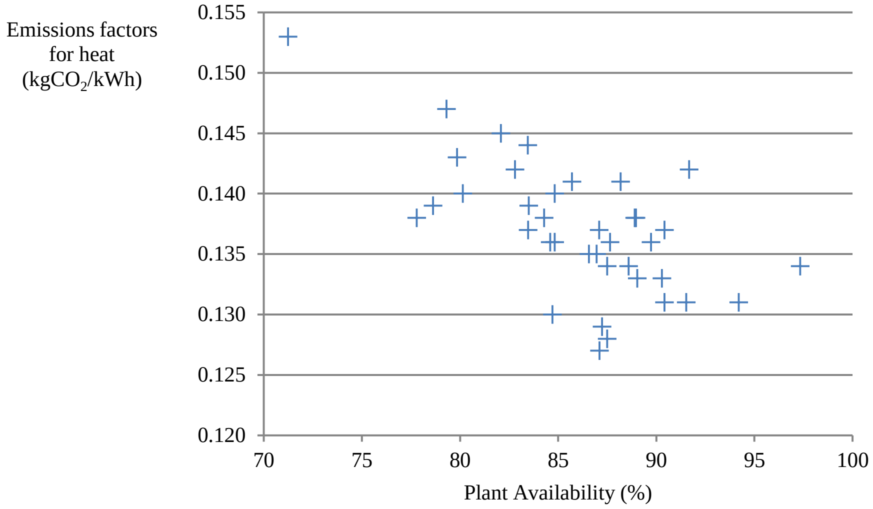

Figure 6-4: The Variation of district heat emission factors according to the monthly ERF availability.

It is clear that a reduction in the availability results in higher emissions figures, while the colder months (with a greater number of degree days) show only marginally higher emissions. There will also be some variability in emissions due to changes in the nature of the waste feedstock according to time of year.

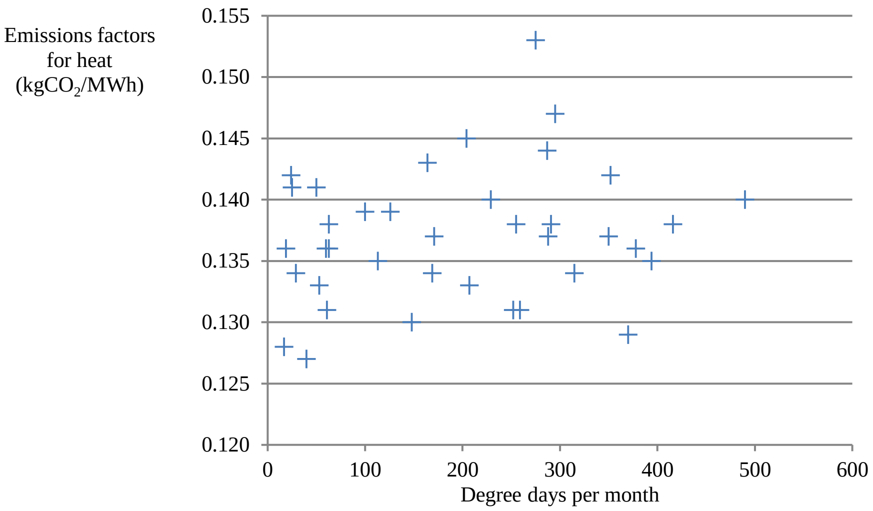

Figure 6-5: The emissions factors for heat plotted against plant availability and the degree days per month. Degree day data is from Degree Days Direct Limited (2013).

6.2.2 ERF Performance

Figure 6-6 and Figure 6-7 show the data for electrical and heat output from the first year of operation of Sheffield's ERF. Higher heat-demand periods in winter coincide with lower electrical outputs from the power station consistent with the trade-off described in Section 3.1.4.

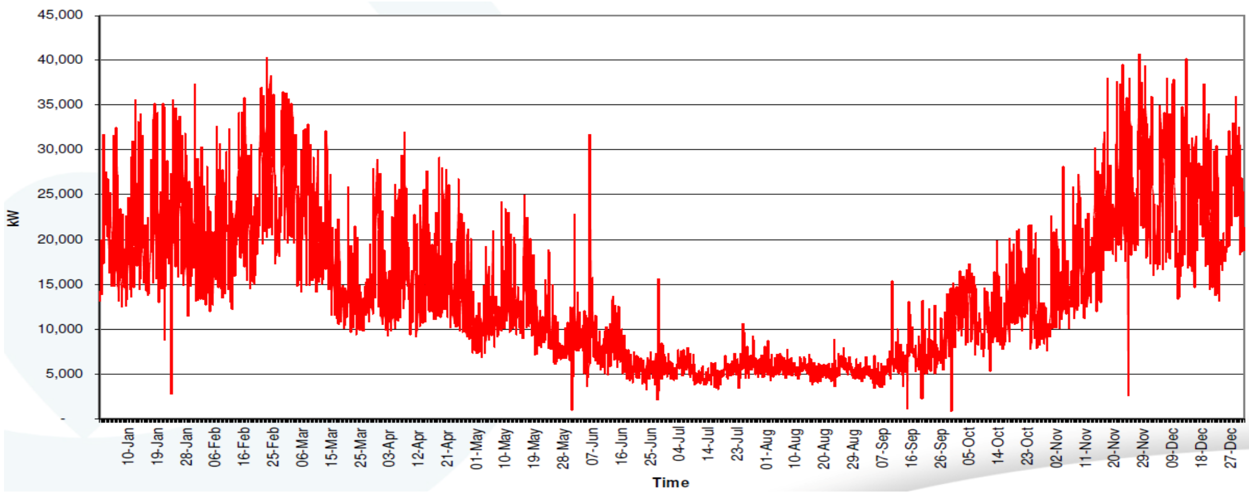

Figure 6-6: Heat exported from the ERF to Sheffield's DH network in 2006.
Source: Veolia Environmental Services (2010).

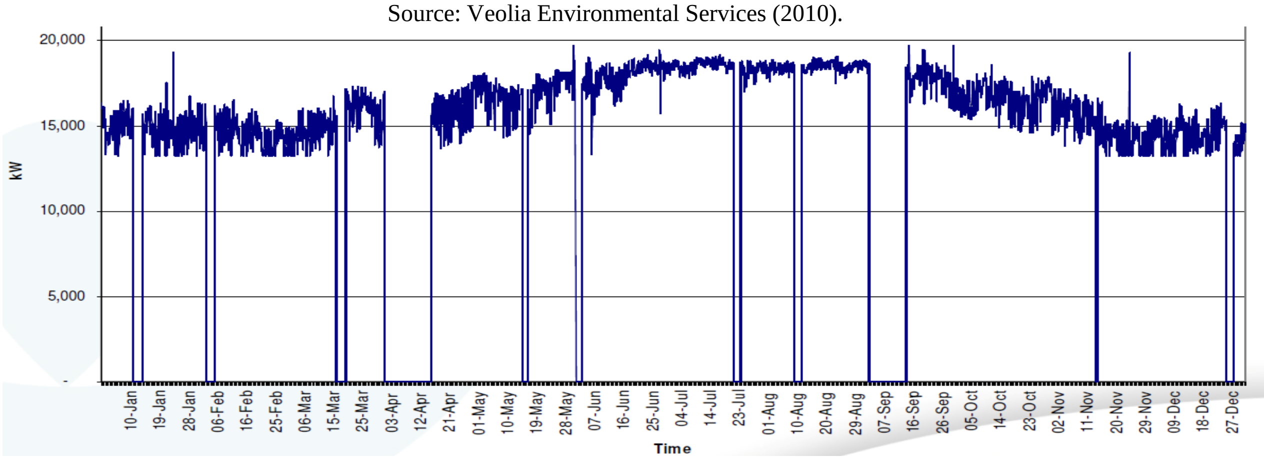

Figure 6-7: Electricity generation at Sheffield's ERF in 2006.
Source: Veolia Environmental Services (2010).

There are anomalous periods in the data set when it appears that the power station may have been switched to high-electricity and low-heat production. The heat outputs where these brief anomalous behaviours occur are not considered representative of the actual network heat demands.

The Sheffield system data shows a greater degree of variability in the rate of heat production over the course of a typical day compared to profiles from Gadd and Werner (2013). This may be representative of Sheffield having a much smaller system capacity since a large network with diverse customer types is likely to have a smoother aggregated variation in demand.

Peak daily heat demand and minimum temperatures

Hourly temperatures for 2006 were available from the Met Office Integrated Data Archive System (MIDAS) database (CEDA, 2015) for a site at Sutton Bonington which is approximately 40 miles south of Sheffield. This was the nearest weather station for which the hourly temperatures were available.

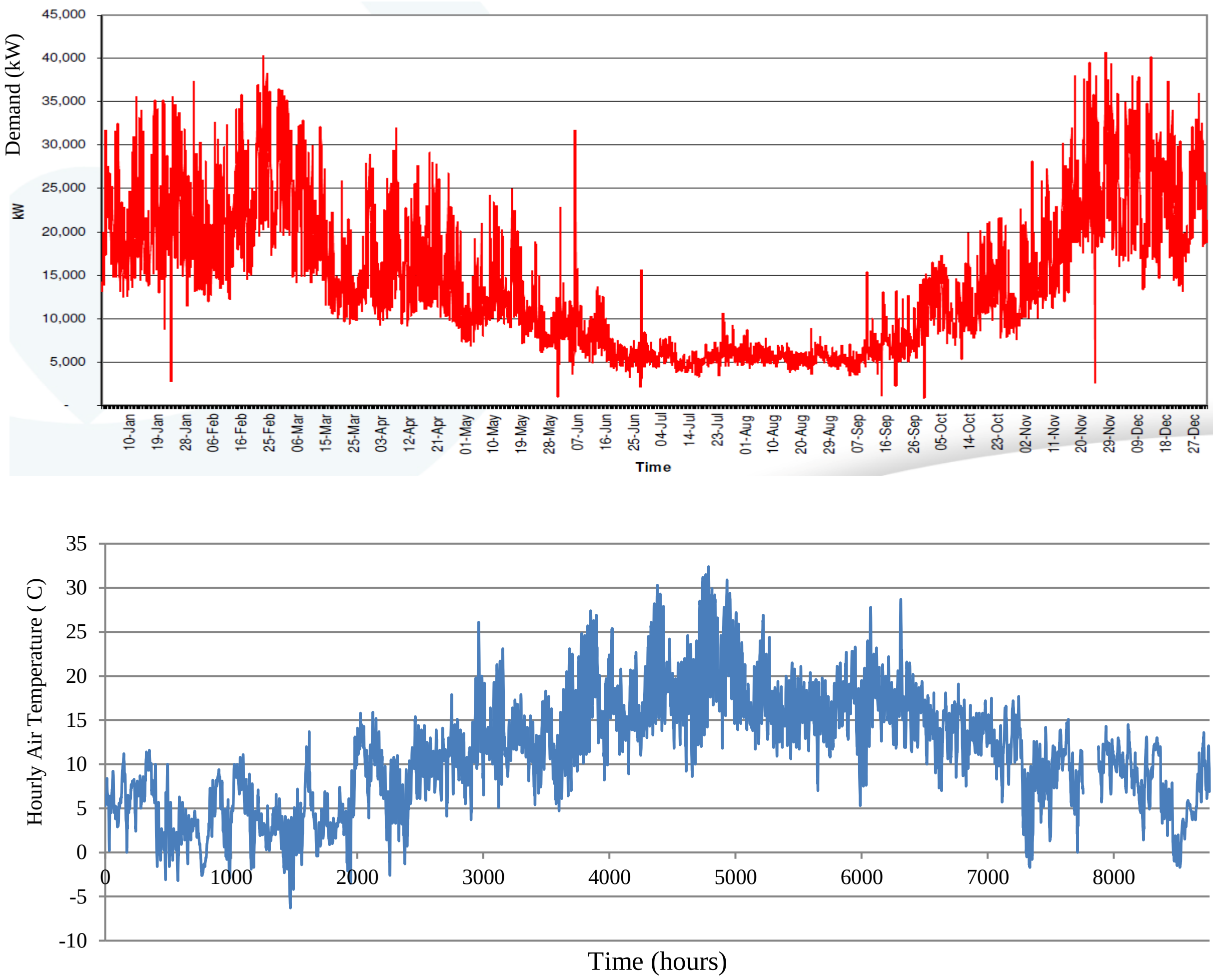

Figure 6-8: Sheffield DH demand and hourly air temperatures recorded during 2006 at Sutton Bonington. Source: MIDAS database (CEDA, 2015).

There appears to be some correlation, however the demand seems higher at the end of the year despite milder conditions than at the start of the year. This may be as a result of additional buildings being served by the network; six buildings were added to the network during 2006 (IT Power, 2006).

Figure 6-8 shows the results of an analysis comparing the minimum daily temperatures seen at Sutton Bonington with the peak daily demands from the Sheffield network. Further analysis to investigate whether the spread in demands was more to do with day of week proved less conclusive.

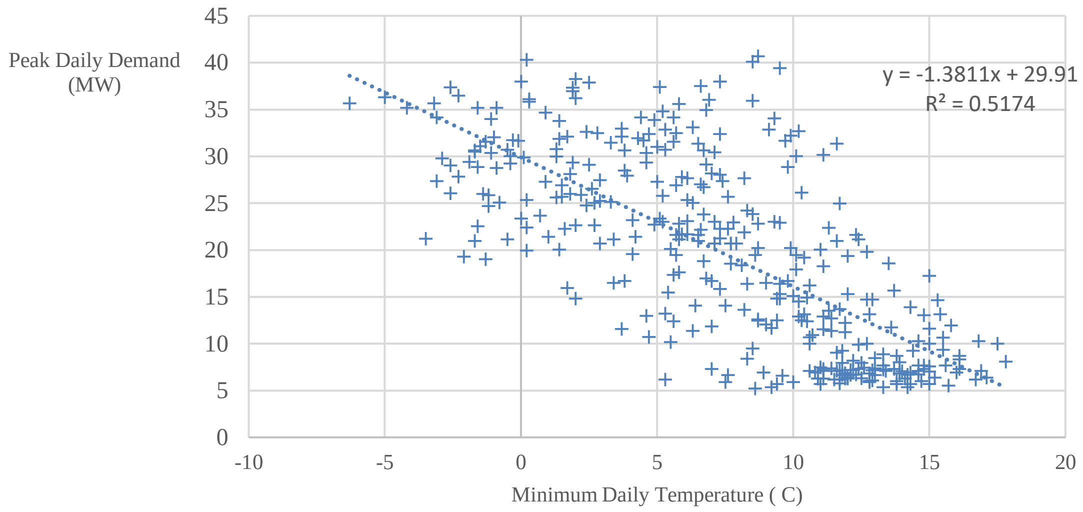

Figure 6-9: The estimated peaks in demand and the minimum daily temperatures at Sutton Bonington campus. Source: CEDA (2015).

Heat and Power Balance

Two series of points, shown in Figure 6-10, were fitted to approximately follow the maximum and minimum values of the heat and electricity outputs. This envelope fits the extremes well and since maxima of heat output coincide with minima of electricity production for a condensing steam turbine CHP plant, and vice versa, then this fit can be useful.

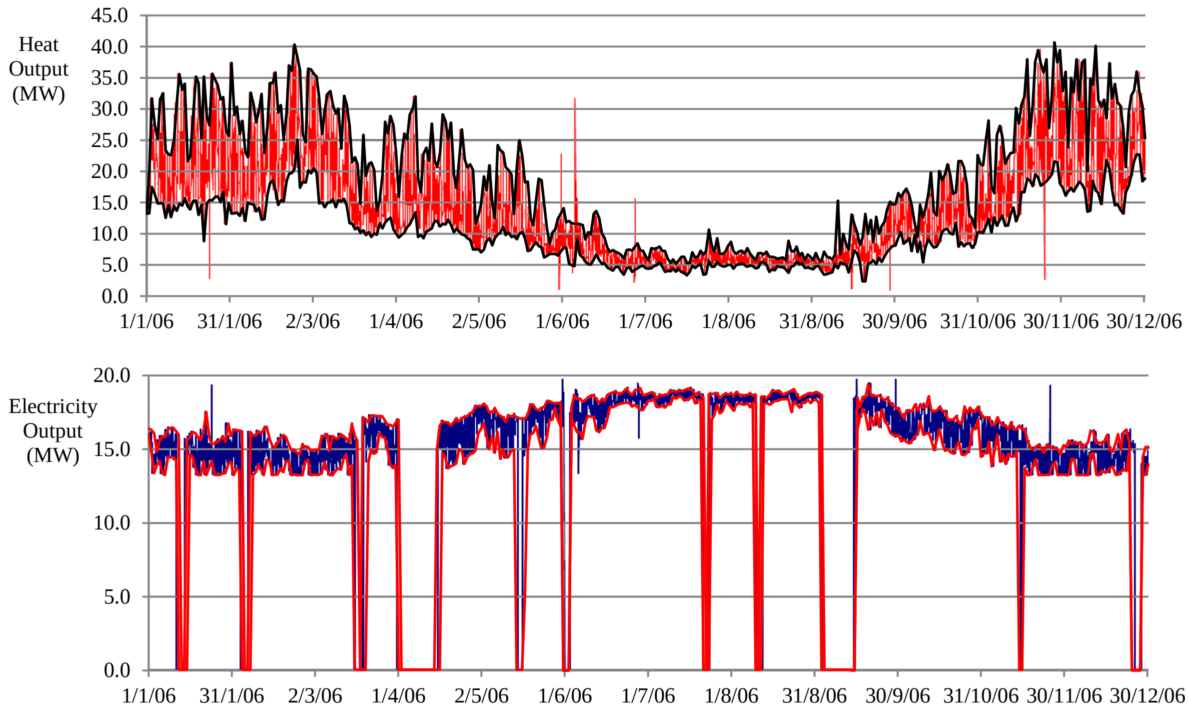

Figure 6-10: The curves spanning the estimated ranges of output fluctuations for electricity and heat from the ERF.

For the ERF, it was assumed that throughout days the balance of heat and power production varies and that maximum heat coincides with minimum electricity production and vice versa. These points were plotted in Figure 6-11 to demonstrate the heat and power trade-off.

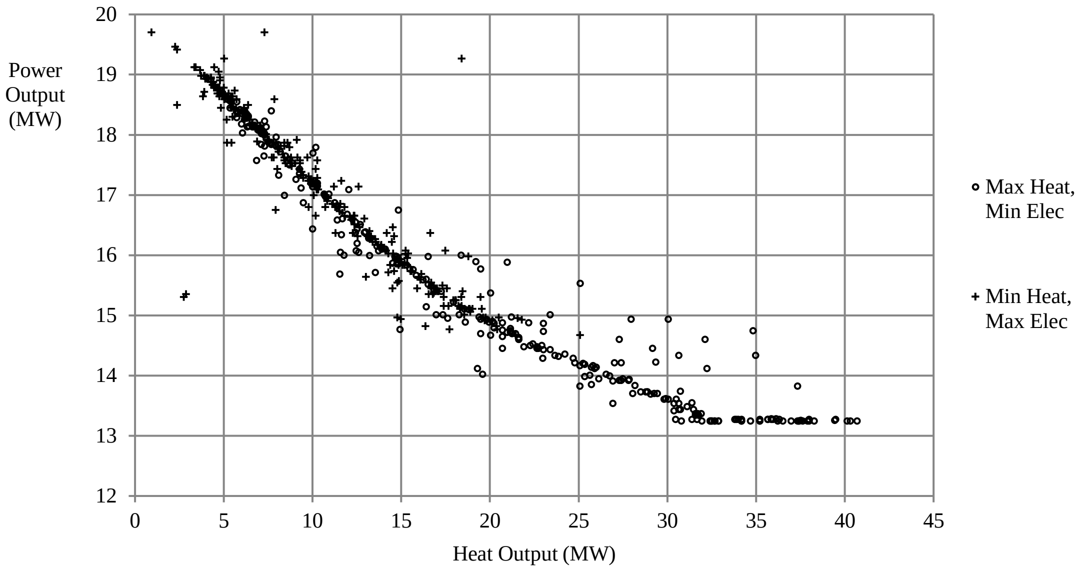

Figure 6-11: Extreme values of heat outputs matched with extremes of electricity outputs.

The changing gradient of the graph is likely due to alteration of the number of steam extraction points used on the turbine as seen in Marchand et al. (1983). In the upper range of heat output the electricity output ceases to fall, instead having a minimum of around 13.2 MW. The thermal capacity of the ERF is noted as 36 MW by Finney (2011) and 39MW by the Environment Agency (2007). It appears here that gas boilers are activated during the short periods during the year when demand is above approximately 33 MW meaning the electrical output falls no further.

For the simulation of the ERF later in this chapter, it was assumed that the trade-off between heat and power followed a linear trend through the following (power, heat) coordinates: (20, 0), (15.2, 18), (13.2, 33), and then any additional heat output above 33 MW comes from additional gas boiler heat.

To give a more representative trade-off between the electricity and heat outputs, the trend of Figure 6-11 is incorporated into the model as two straight line trends covering the CHP outputs between upper and lower limits of heat production.

$$\text{If } (Q<18 \text{ MW}): P = 20 - \left(\frac{4.8}{18}\right) \times Q_{CHP} \text{ [MW]} \tag{6.97}$$

$$\text{If } (18<Q<33 \text{ MW}): P = 15.2 - \left(\frac{2.0}{15}\right) \times (Q_{CHP} - 18) \text{ [MW]} \tag{6.98}$$

$$\text{If } (Q>33 \text{ MW}): P = 13.2 \text{ [MW]} \tag{6.99}$$

The equivalent Z-factors (explained in Section 3.1.4) would then be for the range of heat output [0,18] as given in Equation 6.100 and in the range [18,33] as given in Equation 6.101.

$$Z\ [0,18] = \frac{18-0}{20-15.2} = 3.75 \tag{6.100}$$

$$Z\ [18,33] = \frac{33-18}{15.2-13.2} = 7.5 \tag{6.101}$$

Since there is a factor of two difference between these Z-ratios then there will be also a factor of two step in the marginal cost of heat production since this cost is proportional to the value of lost electricity from increased heat production. There is a point where the NHPC from CHP1 halves since half the amount of electricity is then lost when the demand rises above approximately18 MW.

Primary energy input to the CHP unit, in the form of Municipal Solid Waste (MSW) is estimated to have a calorific value of 510,000 MWh per year and the primary energy input from gas for auxiliary boilers is derived from an assumption of 80% boiler efficiency. Changing definition for CHP boundary for assessment of Good Quality CHP to include the boilers changes the economic case for heat storage.

The actual amount of usage of peaking and back-up boilers can only be accurately established if the DH operator is willing to disclose those figures. In general, CHP operators working under the CHPQA scheme submit fuel use data to AEA for emissions calculations and this is held in confidence (DEFRA, 2012). It seems plausible that the oil and gas boilers at the University and Park Hill boiler houses are deployed as necessary when the DH system is struggling to meet demand rather than simply when demand exceeds 30 MW.

Electricity Production Outages

The periods of electricity production outage from information shown in Figure 6-7 were estimated to add up to around 61 days. The frequency and duration of these outages is shown in Table 6-1 some of these may be days may be where planned maintenance or commissioning-related works were carried out. Also, it seems that unplanned outages usually last for three to four days. The figures in Table 6-1 lead to an estimate of availability of 83% for the CHP plant in 2006 including planned outages.

Table 6-1: The estimated duration and frequency of outage of electricity turbine at Sheffield ERF during 2006.

Outage duration (days)	Frequency	Days of lost production
2	1	2
3	3	9
4	4	16
5	1	5
13	1	13
16	1	16
TOTAL	11	61

Availability of the ERF in the model is assumed to be 86% with outage periods of various lengths including scheduled maintenance periods factored into the calculation. A high availability of the new CHP of 97% for the new CHP plant is used, in line with the expectation of the developers (E.ON UK, 2014).

6.2.3 Electricity Revenue

The ERF supplied electricity under a Non-Fossil Fuel Obligation (NFFO) contract from 2006 to 2013 which had a guaranteed fixed price of electricity at 5.8p/kWh, but in subsequent years will sell electricity at market prices (Kirkman et al., 2010). The actual income will depend upon what type of contract is agreed by the operators. This contract is confidential but is likely incentivise electricity production at certain times of day, for example during day time and triad periods.

NFFOs were replaced in 2002 by the Renewables Obligation (RO) (Ofgem, 2007). Since the feedstock is partly biomass, the ERF qualifies for RO Certificates (ROCs). For 'good quality' energy from waste CHP there is 1.0 ROCs awarded per MWh of qualifying electricity output. The ERF plant also receives income in the form of gate fees for the municipal solid waste (MSW) collection and heat charges for the supply of heat to the DH customers but these two revenues should be unaffected by heat storage and are therefore not modelled here.

The new biomass CHP plant at Blackburn Meadows will have to pay for its biomass fuel but will receive 1.9 ROC incentives for each MWh of electricity generated by good quality CHP due to use of a renewable fuel. The level of incentive for power-only biomass plants is 1.5 ROCs/MWh.

In addition to the ROCs, the plants will both receive revenues for electricity sold to the market. The electricity price for different time periods is important in assessing the advantage of using storage. Figure 6-12 shows the System Buy Prices (SBP) for the UK electricity market in July and December 2012. The prices are significantly higher on average in the winter month, and also vary significantly through the course of the day. Since the contractual prices are not publicly available then the SBP will be used to estimate revenues that can be achieved. This approximation is also used by Toke (2007) for an assessment of CHP economics with storage.

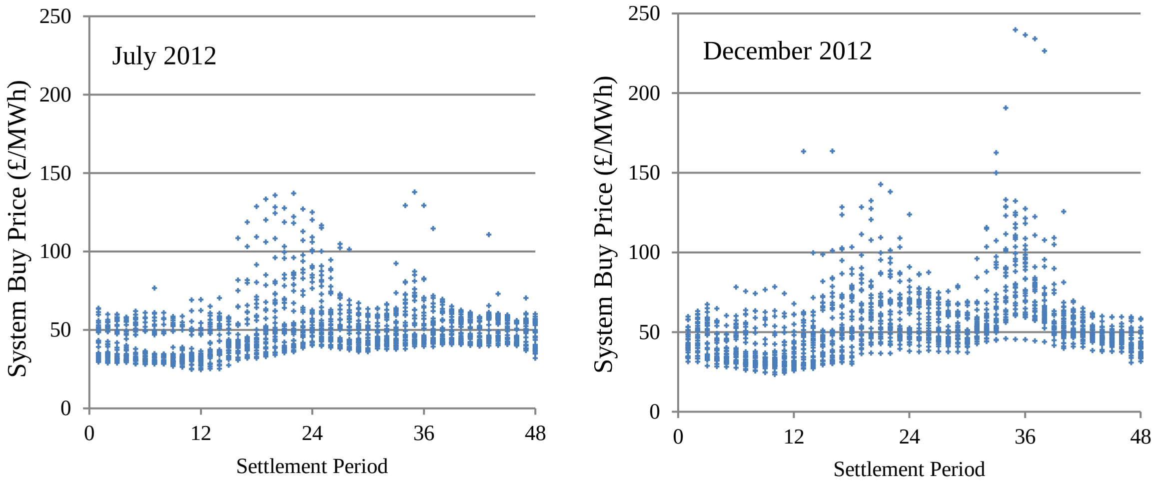

Figure 6-12: System buy prices (SBP) for July (left) and December (right) 2012.
Data source: ELEXON Portal (2013).

Fuels used in CHP, and in some instances the electricity generated, can be exempt from the Climate Change Levy. The case for storing heat for use during unexpected outages therefore needs to avoid reductions in the plant's overall efficiency. By calculating the Quality Index (see Section 3.4.4) it can be determined whether the CCL exemption will be compromised (i.e. if the QI falls below 100).

6.3 Heat Storage Objectives

Increase electricity revenue

Currently the ERF needs to follow the heat demand limiting its capacity to produce electricity at peak-price times due to the trade-off between heat and power production. Heat storage has the potential to liberate the CHP unit from following the heat demand on the DH network. Typically for an extraction CHP unit with a characteristic heat and power production trade-off, a daily heat storage cycle of heat accumulation when electricity is cheap at night and discharge when electricity is expensive during the day would be expected. The pattern will depend upon how the electricity price varies in a particular case.

Incorporation of new CHP units

Thermal stores can assist with the operation of new CHP units to boost efficiency by capturing heat that would otherwise be lost. Small CHP units based on reciprocating engine technology achieve highest efficiency by running at consistent outputs and capturing as much waste heat as possible. There are significant current trends for universities and hospitals to consider the use of CHP and this is true in Sheffield, too.

Co-ordination with the DH operator would be necessary if heat were to be injected into the DH system. However, even with heat storage to smooth variations during the day in summer there is only a limited amount of demand available. The market for selling excess heat from distributed CHP units may easily become saturated and limit the development of CHP by some of these organisations.

Increasing heat network capacity

A heat store could help meet greater peak loads on the network and could also alleviate any bottlenecks in the network pipelines. Charging at off-peak times then discharging during peaks could reduce use of more carbon-intensive heat-only boilers. In winter the charging of the store will depend on there being significant opportunity to charge from a low carbon heat source, such as CHP, at times of day with low demand.

Recent research in the UK indicated almost half of the gas CHP units used heat storage, and that one waste to energy plant found that installing a heat store allowed it to increase the use of the primary source, rather than expensive back-up fuel, such that the store paid for itself within five years (DECC, 2013s).

Resilience of heat supply

It was seen in Section 6.2 that low ERF availability correlates to higher emissions. Hence if a heat store can cover some of the outage period then emissions factors will not rise as much due to heat only boiler use. If part of the network needs to be isolated for maintenance, then a heat store could help to cover heat demands during the outage period.

Cold storage options

Absorption chiller technology using heat from DH could be combined with a cold water or ice store to provide a resilient and economic cooling system. Absorption chillers attached to the DH increase the heat demand in summer with a lesser effect when margins are tight in the winter time. However, absorption chillers may be less efficient than the electrical alternatives (Maraver et al, 2013) and they are difficult to retrofit to existing buildings due to their large size and weight. Cool storage is often deployed with cooling networks for various reasons that benefit the chiller plant, for example by allowing chiller operation at night when air temperatures are lower (Frederiksen and Werner, 2013). Since only a very small fraction of the Sheffield DH supply is used for absorption chillers, the use of cool energy storage is not further considered in this study.

6.4 Chosen Heat Storage Technology

Having assessed a wide range of thermal energy storage technologies in the Literature Review, large hot water accumulators remain the preferred method for heat storage in most DH scenarios as described in Section 2.5.1.

In Sheffield, hot water is transmitted through the network at around 110°C. Having such a high supply temperature does benefit heat storage since a large difference between supply and return temperatures results in a smaller volume of storage required for holding the same energy. A water temperature of 110°C is too high for plastic containers so metal, concrete or similarly resistant materials would be required for containment. Variation in the supply temperatures is already used occasionally to store heat in the city-centre network itself. The way heat is stored in the buildings connected is very interesting but quite a complex matter that is beyond the scope of this work.

Example: The Lower Don Valley transmission pipe as a heat store.

The new DH pipe from the biomass CHP unit at Blackburn Meadows that features in Chapter 5 is designed as a ‘spine’ for future networks to branch off with the potential to carry a significant amount of heat towards the city-centre heat network.

The pipeline has two DN350 pipes running in parallel and any variation of supply temperature could be used to store heat in that pipeline. The pipeline connecting to the city centre network would be approximately 6.5km in length, giving a volume V in each pipe as in Equations 6.102 to 6.104.

$$V = \pi \frac{d^2}{4} l, \tag{6.102}$$

$$V = \pi . \frac{0.35^2}{4} . 6500, \tag{6.103}$$

$$V = 625 \text{ m}^3 \tag{6.104}$$

If this capacity could be used to store energy by raising its temperature by 5°C, then an energy capacity given by Equation 6.108 would theoretically be available.

$$E = \rho . V . c . \Delta T \quad (6.105)$$

$$E = 960\text{kg/m}^3 . 625\text{m}^3 . 4.2\ \text{kJ/kg.K} . 5\text{K} . \text{Wh/3600J} \quad (6.106)$$

$$E = 960 \times 625 \times 4.2 \times 5/3600\ \text{kWh} \quad (6.107)$$

$$E = 3500\ \text{kWh} \quad (6.108)$$

A temperature swing of more than 5°C is possible but large temperature swings may reduce the lifetime of the heat network due to thermal cycling of components. It is also worth noting that limits of speed of water in the network of 3 m/s should be observed and therefore a 6500 metre length of pipe would take 36 minutes to charge or discharge meaning a limit to the charge rate of just under 100 kWh per minute or 6 MW. Furthermore if the charging of the pipe is intermittent as the water is being circulated then not the whole length will have the hotter water in and so the capacity would only be partially used. This begins to illustrate the complexity of the charge and discharge but that does not mean that this mechanism should be neglected.

6.5 Modelling Heat Store Operation

Currently in Sheffield DH, the heating plant matches heat demand from the DH network on a moment-to-moment basis. This means maintaining a constant supply temperature for distribution given different levels of water flow through the network varying according to demand. The aim of these simulations is to develop a control strategy resulting in better economic and/or environmental outcomes for meeting the heat demands on the network.

6.5.1 Quantifying Heat Demand Variation

The 2006 data from the Sheffield ERF in Figure 6-6 was indicative of the maximum and minimum of heat demands each day, but not of the shape of demand variation during each day. The heat demand variation of the network was simulated by scaling the variation of the demand seen in Chapter 4 for the University of Sheffield campus by an appropriate factor to represent the whole city wide network heat demand.

Figure 6-13 shows a comparison of maximum and minimum daily loads simulated for 2012 compared with the actual minimum and maximum load pairings seen in the 2006 data. The spread of data points appears similar in distribution with the exception that the cluster of points during the low heat demand period (summer) are generally higher than the simulated numbers. This will reflect the fact that the 2012 simulation is based on the amount of heat that reached the consumers while the actual 2006 load will also include an additional near-constant base load for heat losses on the network. There are also some anomalous points in the 2006 data possibly reflecting occasional outages of the CHP where the heat production has quickly dropped below that expected and is not representative of the heat load.

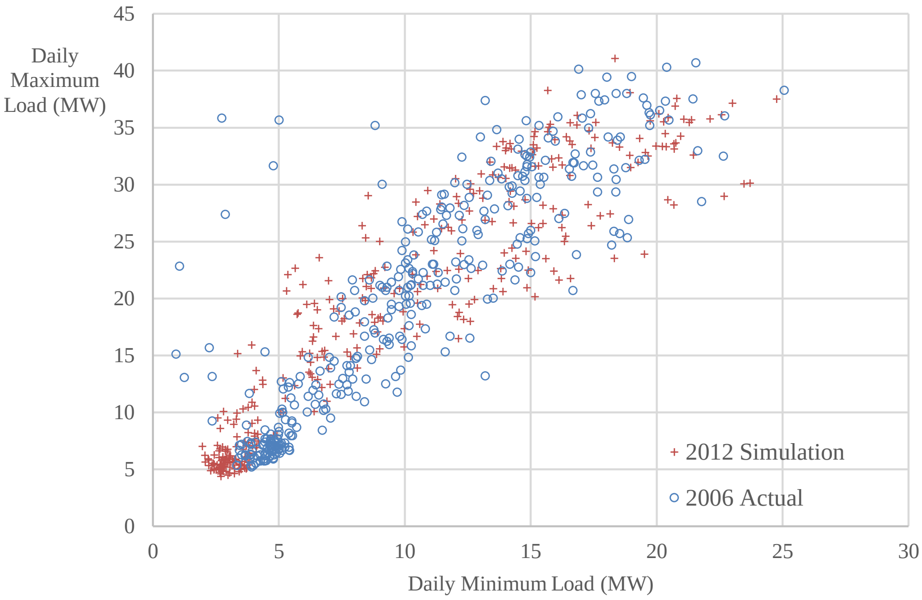

Figure 6-13: Comparison of daily minimum and maximum loads from the simulated and actual data for the city-centre network.

6.5.2 Modelling Heat Sources

Equations 6.100 and 6.101, describing the heat and power trade-off investigated in Section 6.2.2, was used to calculate the corresponding electricity outputs for each level of heat demand at the ERF. In the models including the CHP at Blackburn Meadows, the trade-off between heat and power was as described in Chapter 5. The running priority of the different heat sources will be determined by a net heat production cost calculation that will be described in Section 6.5.4.

6.5.3 Environmental Analysis

The results will be presented along with the overall impact on carbon dioxide emissions. In general, the reduced use of gas boilers in favour of use of CHP heat will lead to lower emissions. The impact of exporting more or less electricity to the grid is considered with respect to the carbon emissions from the marginal power plant as described in Section 3.6.4. Reduced use of gas boilers results in a reduction in carbon emissions as described in Section 3.6.1.

6.5.4 Economic Analysis

Net Heat Production Costs

In chapter 5, it was assumed that the industrial waste heat should be prioritised over heat from CHP which was itself prioritised over the use of gas boilers. There was an implicit assumption in this approach that the cost of heat production rose in that order. For extraction-condensing CHP units, the net cost of heat production includes any lost electricity revue from greater heat production.

In this final stage of modelling the net heat production costs (NHPCs) were explicitly calculated and compared by the model in order to choose to extract heat from the CHP with the lowest net heat production cost as a priority. For the heat from gas boilers the net heat production cost was simply the cost of gas fuel divided by the efficiency of the gas boilers on a gross calorific value basis. For the CHP units, the fuel input is assumed not to change as that is true in the given application and as a result the corresponding net heat production cost is found by calculating the value of lost electricity income. The parasitic consumption of electricity is assumed to be equal in the different scenarios and the turbines are still operating, however there will be a small difference in the electrical consumption for pumping of DH water depending on where the heat is sourced from but this is neglected here.

In the model, which has its C++ code in Appendix 10.5.4, the NHPC calculation appears as a function similar to that below.

```
NHPCCalc(NHPC,Av,Q,CHP1.Max,R100,RVal,Price,ERF(Q,Av),ERF(Q+dCHP,Av),dCHP);
```

The function has reference to the maximum thermal output of the CHP unit, providing an upper limit on heat output, and there is reference to the quantity and value of ROC certificates and the market price that the electricity being produced by the CHP would have made. The function has a sub function ERF(Q,Av), or BM(Q,Av) that calculates the electrical output for a given heat output, Q, at the Energy Recovery Facility CHP or Blackburn Meadows CHP as described in Section 6.5.2 above or chapter 4. The NHPC calculation is calculated as in Equation 6.109.

$$\text{NHPC} = (R_{100} \times R_{value} + Price) \times \frac{[P(Q) - P(Q + dCHP)]}{dCHP} \ [£/\text{MWh}] \tag{6.109}$$

Where NHPC = Net Heat Production Cost;

R_{100} = number of ROCs granted for a MWh of electricity at QI ≥ 100;

R_{value} = value of a ROC;

Price = the spot market price for electricity at the time of production;

P(Q) = the power output with a given heat output, Q.

Since the number of ROCs given for biomass CHP is greater than energy from waste then the first factor of heat production cost is greater for the biomass CHP, however the differential in power output for taking a unit of heat is lower for the biomass CHP due to a higher Z-ratio. As a result there is a complex calculation to do to choose the lowest NHPC heat source.

In circumstances where the heat output increases with electrical output, rather than the steam turbine trade-off applicable here, if there is sufficient benefit in producing the extra electricity then the net heat production cost can be negative and it is worth either dumping that heat to atmosphere or contributing to displace heat from other higher cost sources on a DH network. These NHPCs will be used to determine when to add heat to a heat store and when to discharge the store to achieve best value.

6.6 Case Study Simulations

The information gathered at earlier stages of the project, along with updated information, regarding the city-wide heat network was used to modify the model from Chapter 5 to model the city-centre network as it currently operates and then to connect the existing network with the new network development described in Chapter 5. One of the complexities of adapting the code was to account for the complex trade-off between heat and power production for the steam turbine, as explored in Section 6.2.2.

6.6.1 City-Centre Network Only

Energy centre output to DH is modelled as 120,000 MWh per year as this is the current level of demand, the exact level varies depending on the weather in a year. The storage control algorithms are the same as those described in Section 5.4.8. Various heat storage capacities are modelled and make use of CHP heat to displace gas boilers. These assumptions in the model lead to results in Table 6-2.

Table 6-2: Results from the city-centre network model.

Heat store capacity (MWh)	Annual store heat losses (MWh)	Change in CHP electricity production (MWh/a)	Change in CHP heat production (MWh/a)	DH heat from gas boilers (MWh/a)	Quality Index, QI	Net change in CO_2 emissions (tCO_2/a)
0	0	0	0	15,559	116.86	0
5	53	+517	+221	15,391	117.28	-210
10	106	+971	+380	15,285	117.64	-385
15	159	+1,124	+531	15,187	117.78	-458
20	212	+1,154	+678	15,093	117.84	-490
25	265	+1,197	+811	15,013	117.91	-523
30	317	+1,219	+961	14,915	117.96	-552
35	369	+1,218	+1,098	14,830	118.00	-572
40	421	+1,226	+1,237	14,743	118.04	-595

The results in Table 6-2 are counter-intuitive as, on first impression, the increased heat from CHP should result in a reduction of power output. However, another process is also at play where the presence of heat storage is allowing the steam turbine to operate in more efficient range than is possible without heat storage. Figure 6-14 demonstrates this principle by showing the divergence of heat outputs while noting that heat storage allowing a reduced heat output in the lower range and an increased heat output in the higher range leads to a net gain of electricity for the same amount of heat production. The point of inflexion regarding the Z-factor was highlighted in Figure 6-11 and in associated equations 6.100 and 6.101.

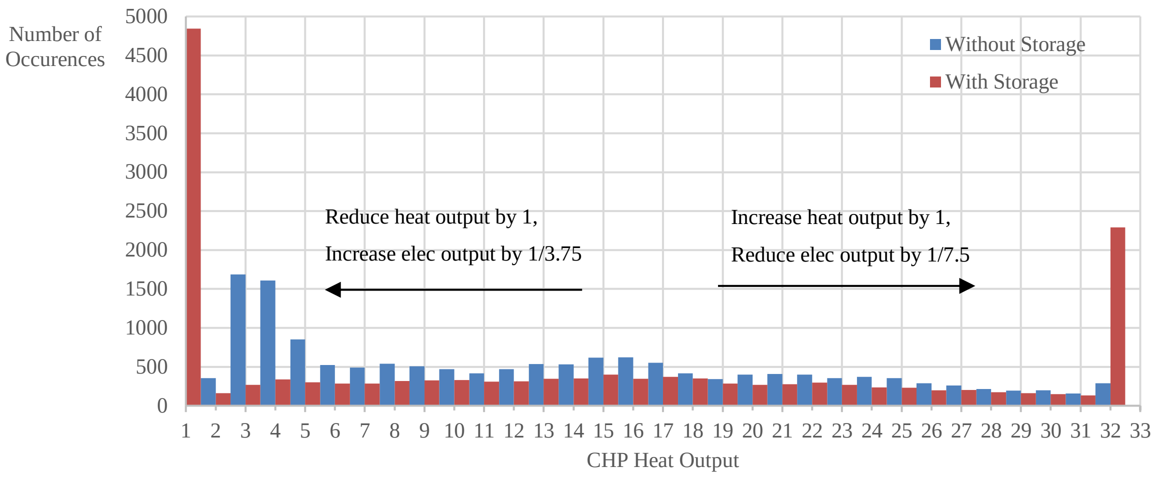

Figure 6-14: The divergence of heat output values at different times through introduction of 40MWh of heat storage.

The simulated heat from gas boilers makes up 13.0% of the demand. There is higher electricity production overall but this is only approximately 1% of the annual total electricity production. The use of heat storage allows greater electricity production at peak price times, too. There will be more ROC certificates received by the plant due to greater overall electricity production.The additional electricity revenue benefit is significant as seen in Figure 6-15.

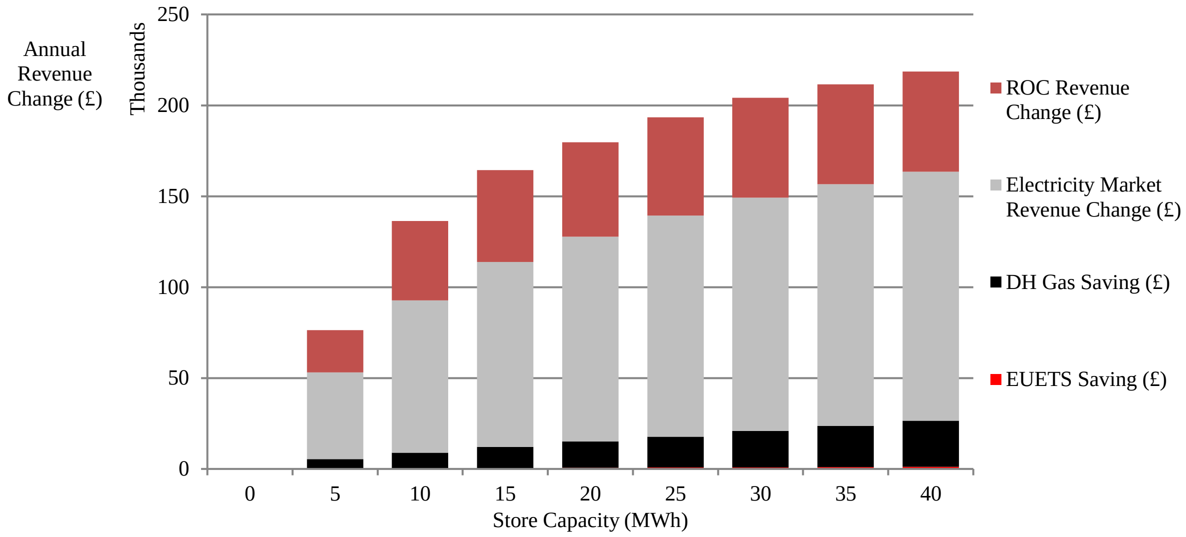

Figure 6-15: Economic results from simulation of the city-centre network.

The savings attributed to carbon savings under the EU ETS are present in Figure 6-15 but only have values of up to £1135 and are almost too small to register on the graphs. Future rises in the carbon price would result in greater saving from the EU ETS. The main component of the saving is through using the store to increase electricity market revenue in the spot market.

6.6.2 Connected Heat Networks Without Heat Storage

The connection of two DH schemes together is assumed to bring an additional 30,000 MWh of heat load to the network initially and in the model there are now two CHPs that can contribute heat to meet demand. The sourcing of heat was done for each half hour by calculating the cost of heat production due to reduced electrical output and corresponding reduction in the number of Renewable Obligation Certificates (ROCs) as a consequence of diverting steam from power production to the production of heat. Figure 6-16 shows the calculated contribution of the two CHP units and the gas boilers depending upon demand and CHP availability. 'CHP1' refers to the energy from waste CHP and 'CHP2' refers to the biomass CHP unit. The code used to calculate this distribution is included in Appendix 10.5.4.

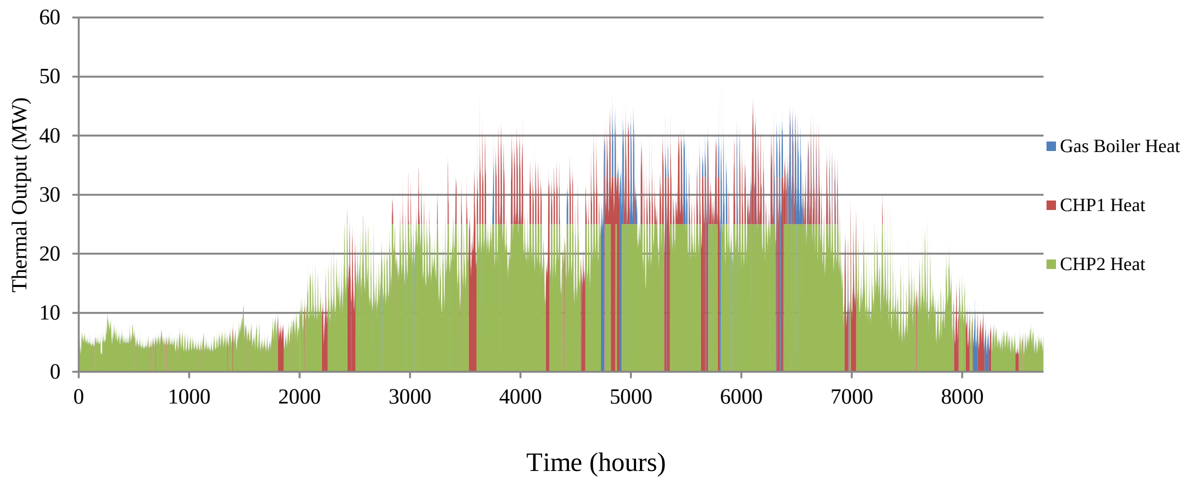

Figure 6-16: Contribution of the heat sources to meeting demand without heat storage.

The supply from the CHP2 dominates due to a higher Z-ratio meaning lower effective costs for heat production despite a higher value for electricity due to a greater number of Renewable Obligation Certificates being awarded. Table 6-3 shows the changes in electricity and heat production and the changes to QI from going from two separate networks to a combined one.

Table 6-3: Comparison of existing and connected networks without heat storage.

Scenario	CHP1 electricity production (MWh/a)	CHP1 heat production (MWh/a)	CHP2 electricity production (MWh/a)	CHP2 heat production (MWh/a)	DH heat from gas boilers (MWh/a)	CHP1 QI	CHP2 QI
City-centre only	128,297	104,441	n/a	n/a	15,559	116.86	n/a
LDV only	n/a	n/a	265,977	29,033	967	n/a	95.71
Connected	147,696	26,168	219,658	115,552	8,280	113.54	104.59
Change	+19,399	-78,273	-46,319	+86,519	-8246	-3.32	+8.88

From the table, it can be seen that connecting the two networks will result in 8246 MWh of heat from gas instead being supplied from CHP due largely to the ability for one CHP to cover heat supply during outage at the other. In combination with 26,920 fewer MWh to grid, the overall carbon impact is actually positive as shown by Equation 6.110. For context, this result compares to approximately 100,000 t CO_2 of annual savings by the two CHP units being in operation.

$$\text{Net change in } CO_2 \text{ emissions} = +0.339 \times 26{,}920 - 0.18521 \times \frac{8246}{80\%} = +7001\ \text{t} \qquad (6.110)$$

This result may be surprising, but the increase in heat extraction from CHPs means a better economic outcome but the current high carbon intensity of grid electricity means that the resulting lower level of electricity production to grid overall has a greater impact on overall carbon emissions. If the carbon intensity of grid electricity falls to 0.071 kgCO_2/kWh, exceeding UK government projections for 2030, then the connection of the networks would have a neutral impact on CO_2 emissions.

6.6.3 Connected Heat Networks With Heat Storage

It was a complex matter to alter the code developed for the work in Chapter 5 in order to model a connected network, resulting in the extensive code of Appendix 10.5.5. To economically optimise the supply of heat the net heat production costs (NHPCs) had to be repeatedly calculated by the simulation code for the two CHP plants. Heat losses from the heat store at various levels of stored energy were factored into the analysis as was the case in earlier simulations. Figure 6-17 and Figure 6-18 show the variation of heat sources and heat storage over a sample period of the modelled year.

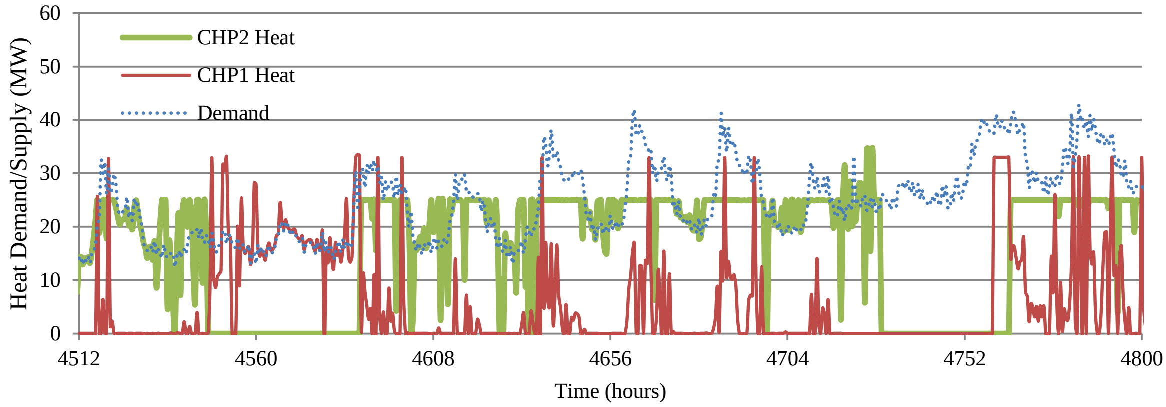

Figure 6-17: Heat production from different sources over six days in the combined networks model.

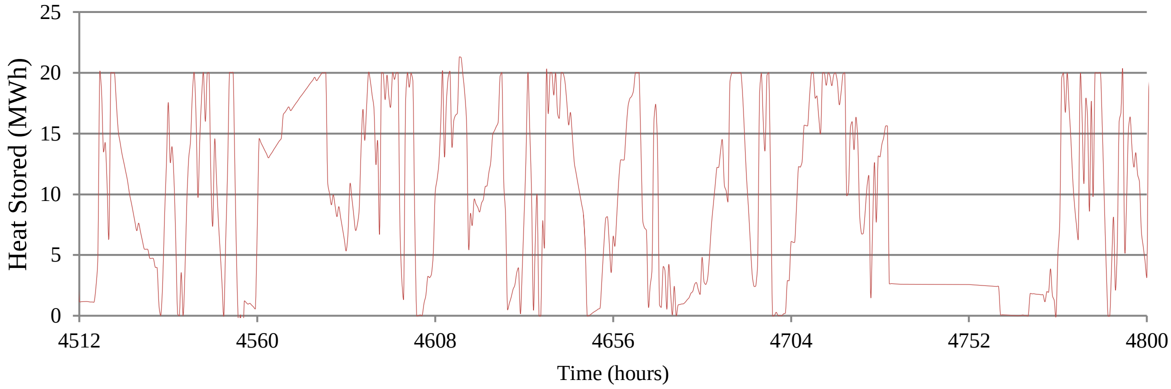

Figure 6-18: Level of stored energy over six days in the combined networks model with 20MWh store capacity.

In general, CHP2 has a lower NHPC, but there are periods where CHP1 takes over due to outage at CHP2. If the demand exceeds the capacity of CHP2 to provide the heat CHP1 can contribute heat at a lower cost than gas boilers. Spikes in heat output overnight shown in Figure 6-17 correspond to low price periods where the model has scheduled high heat production levels to maximise the low cost of heat production at that time. Table 6-4 shows the incremental changes of the CHP outputs as well as the level of gas boiler use with various amounts of heat storage on the network.

Table 6-4: Results for a connected network.

Heat store capacity (MWh)	Annual store heat losses (MWh)	Change in CHP electricity production (MWh/a)	Change in CHP heat production (MWh/a)	Change in CHP electricity production (MWh/a)	Change in CHP heat production (MWh/a)	DH heat from gas boilers (MWh/a)	CHP1 Quality Index	CHP2 Quality Index	Net change in CO_2 emissions (tCO_2/a)
0	0	0	0	0	0	8,280	113.1	104.6	0
5	58	-171	1,117	81	-145	7,367	113.3	104.6	-182
10	112	-275	2,251	288	-711	6,852	113.5	104.6	-335
15	164	-385	3,413	457	-1,347	6,379	113.7	104.6	-464
20	217	-449	4,060	570	-1,763	6,200	113.8	104.6	-522
25	269	-482	4,507	614	-1,918	5,960	113.9	104.6	-581
30	322	-622	5,391	750	-2,436	5,647	114.0	104.5	-652
35	372	-692	5,918	832	-2,706	5,441	114.1	104.5	-704
40	423	-689	6,216	894	-2,867	5,355	114.2	104.5	-745

The economic results for the interconnected networks with heat storage are shown in Figure 6-19. At 5MWh of heat storage, the change in ROC revenue is slightly negative due to switching of CHP energy balance from electricity to heat production to displace gas boilers while at greater store capacities there is increased movement towards maximisation of ROC revenue across the two CHPs.

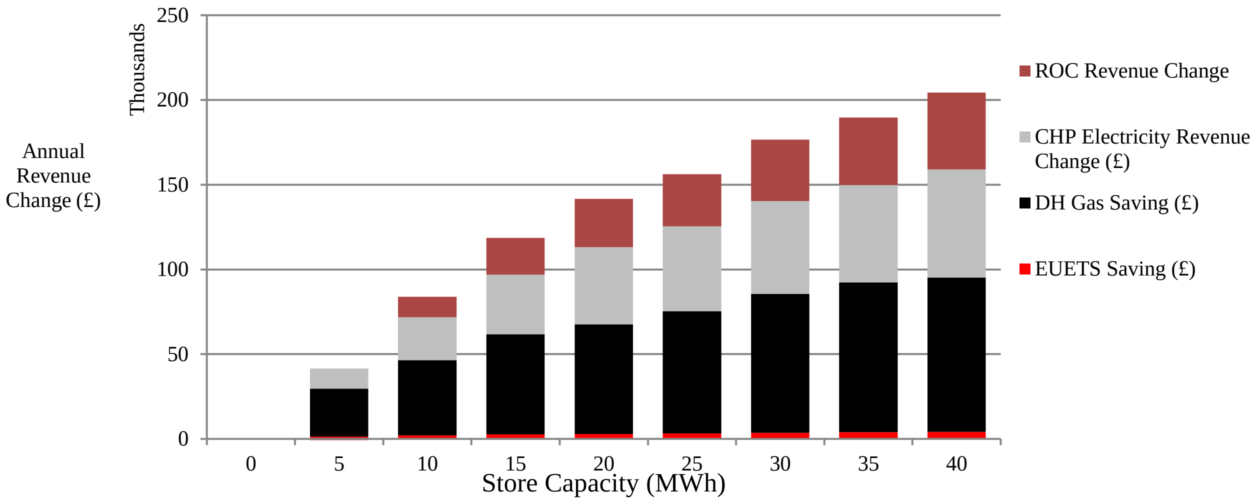

Figure 6-19: Economic results for interconnected heat networks with heat storage.

Figure 6-19 shows a lower rate of return for heat storage on the interconnected networks compared to adding heat storage to the city centre network as in Figure 6-15 due to greater gas boiler displacement potential for the city-centre network before interconnection.

6.7 Summary and Conclusions

The negative correlation between Energy Recovery Facility (ERF) availability and the carbon emissions factor for district heating supply was demonstrated in Section 6.2.1, consistent with the use of fossil fuel boilers to cover outages at the ERF. There was also a weak positive correlation of the emissions factor with the number of degree days per month due to the use of boilers for top-up heat as well as heat during outages during the cooler months.

Study of heat load patterns for Sheffield DH in 2006 compared to the nearby air temperatures indicated the need to allow for growth or shrinkage in the number of network customers over time. It was also possible in Section 6.2.2 to used data from the ERF to accurately characterise the trade-off between heat and power production in order to build an appropriate computer model for the city-centre network.

The possible benefits of deploying heat storage were explored in terms of incorporating a buffer tank or even using the capacity of the pipes themselves although the complexity of the charge and discharge process for the latter led to its exclusion from further modelling.

The computer model of Chapter 5 was applied to the city-centre heat network in order to evaluate the benefits of heat storage. The algorithm was further developed in order to model a connected network with two CHP units with differing costs of heat production and allowing for different volumes of heat storage to be incorporated.

The main environmental and economic advantages are when the heat storage can reduce the need for peaking boilers fired with expensive fossil fuels. This was particularly the case for the current city-centre network but the advantages in this respect were seen to diminish if there is interconnection of the two heat networks. The reason for this is that gas boiler use is already significantly reduced if there are two CHP that are able to cover periods of outage at each other. The incremental benefits for additional store capacity reduced with increasing store size.

The economic case for moving electricity production into the daytime was less clear because of secrecy surrounding the prices which power stations can achieve for selling electricity. Therefore spot market prices were used to judge the benefit of altering heat production timing.

7 DISCUSSION

The modelling of three case studies in Chapters 4, 5 and 6 has explored opportunities for heat storage to play a role in achieving better energy management. This section discusses the assumptions and outcomes from the modelling of these case studies to understand the significance of results achieved. The discussion is structured as follows.

Regarding the understanding of the existing energy systems, the discussion covers:

- District heating demand profiles;
- Combined heat and power unit operation;
- Industrial energy use estimations;
- Revenues for heat and electricity.

Regarding the understanding of heat storage, the discussion covers:

- Choice of technology;
- Efficiency of storage;
- Store control strategies;
- Store charging capacity;
- Locations of storage;
- Carbon savings.

7.1 Understanding of existing energy systems

7.1.1 District heating (DH) demand profiles

The nature of heat demand variations in DH networks is critical for understanding the potential benefit for the incorporation of heat storage. From the Literature Review, such demand data was found to be very limited. The demand profile will affect how the store can help with meeting the peaks in demand, with a recharging possibility during the day. The common double-peak shape during the day is due to movements of people between places of work and residences hence there are important social factors affecting the demand shape.

In Chapter 4, half hourly heat demand data was available for most of the buildings at the University allowing for an accurate description of heat demand variation. In Chapter 5, the half-hourly variation of heat demand from Chapter 4 was used as the basis for the demand variation of the DH scheme. Since there was an inevitable uncertainty in the variability of heat production from industry then this demand variation is likely to have given a sufficiently accurate estimate of the actual heat demand variation. Since the Lower Don Valley heat network is in the process of commissioning there is still uncertainty over which heat loads will connect in which order meaning it is difficult to predict the likely heat demand variation. In Chapter 6, the heat demand variation data from the University was used again to give a variable demand profile for the city-wide networks. Graphs showing demand variation in Sheffield's city centre network through the course of 2006 was available, but data concerning the variations of demand during the course of a day was not. The diversity of building types on the network will have an important effect on the hour-by-hour variation due to differences in demand profiles for offices and residences and other building types; the range of building types on Sheffield's DH network was seen in Figure 6-1.

7.1.2 Combined heat and power (CHP) unit operation

In Chapter 4, various reciprocating engine CHP and heat storage options were modelled. Initial modelling considered non-modulating CHPs, however operation of such engines for short periods is unrealistic due to increased maintenance requirements and for this reason engines typically can modulate down to 50%. The best economic value is likely to come from matching the site electrical loads to achieve high electricity bill savings. This will likely mean some rejection of heat when the heat demands from buildings are low.

In Chapter 5, there are more assumptions about the performance of the steam turbine based on initial test of the turbine in electrical output only mode since the heat network had not yet been commissioned and also using an assumption of the Z-factor as given by the plant developers. When the network becomes operational some of the performance characteristics will depend on the return temperatures from the heat network customers and therefore while the network is growing there will be uncertainty over some of these parameters. However, the current assumptions used provide the best basis for modelling.

In Chapter 6, data was used to derive the trade-off between electricity and heat from the Energy Recovery Facility turbine. This revealed the peak heat output from the turbine to be lower than expected with the remainder from additional fossil fuel boiler use above around 33 MW of thermal output. A correlation of increased emissions factors to colder temperatures was seen in Section 4.2.1 indicating use of the top-up boilers. However the weakness of this effect may be due to overall dilution of emissions per unit heat by the fact that the ERF is also selling a lot of heat under winter conditions at all times of day.

7.1.3 Industrial energy use estimations

In Chapter 5, the inventory of energy inputs and outputs for the industry site were constructed partly from some energy use data made available but also using data from similar documented industrial systems. The biggest factor in determining the level of waste heat available will likely be the level of steel production that is scheduled which varies from year to year. The technical assumptions have been carefully considered but uncertainty over flow temperatures and volumes for cooling water and flue gases could still affect effectiveness of heat recovery.

The balance between sensible and chemical energy in the off-gases was found to be an important variable, and this depends upon the nature and location of combustion processes in the furnaces. Ideally, only a low amount of CO and H_2 would emerge in the flue gases and instead the sensible energy will be a greater proportion giving greater potential for heat recovery.

The variability of heat demand for space heating on the industry site was very strong and accordingly the levels of demand in winter months will be hard to predict and manage if that pattern continues. This demand level is important for determining how much heat can be sold to the heat network.

7.1.4 Revenues for heat and electricity sales

For a CHP installation, the trade-off between electricity and heat production has economic consequences making optimisation a question of engineering and economics. An important part of the economic assessment is the market price for heat that can be found via district heating. Since natural gas is the dominant heating means in the UK market, the price of heat will need to be competitive with this in order to convince customers to join.

In Chapter 5, it is important to note that the responsibility for balancing heat supply and demand on the network would remain with the DH operator. Introducing intermittent heat from industry reduces the operational flexibility of the scheme. It was established that the amount of heat power available from industrial waste heat boilers may be too much to direct into the system in summer-time when demands are low on the network leading to heat rejection to atmosphere and reducing the economic and environmental benefits. Access for industrial waste heat from other sites and CHPs that reject heat into the network will also be limited by the heat demand.

In Chapter 6, there was financial gain from time-shifting of electricity production; this will be balanced against the necessary increase in capital costs of having heat storage. The variation of electricity prices according to time of day was estimated from spot prices. In reality the electricity generated will be traded in a number of ways depending on what achieves best value, for example producing the maximum amount of generation at times of peak electrical demand may be encouraged by incentives. It is interesting to note as well though that the income of Renewable Obligation Certificates for electricity generated from waste or biomass reduces the relative incentive from the market price as a share of overall electricity income.

7.2 Understanding of Heat Storage

7.2.1 Choice of Technology

Only hot water storage has been applied in the energy system modelling work. There are inherent inefficiencies involved in heat transfer processes that give advantage to the storage of hot water in order to produce heat as required by district heating compared to the transfer to another medium. In the case of industrial heat recovery, the initial heat-carrying medium could be stored, for example steam, cooling water, or flue gases, subject to certain limitations. For example, flue gases are very high temperature but they have very low densities too and thus storage of these large volumes is deemed unfeasible.

Other options for thermal energy storage were explored in the Literature Review, including phase change materials but studies into these materials highlighted inhibitive practical problems with the materials. For example, phase change materials are often constrained on power of charging and discharging due to low thermal conductivity. Stratified water stores are only suitable for stationary applications as too much mixing would occur in a partly charged transportable store.

7.2.2 Efficiency of storage

The model in Chapters 4 assumed 100% round-trip efficiency for the heat store; this is unrealistic since there will be heat losses through the container wall, as well as hot and cold water mixing in a water tank. There will be a trade-off between the cost of insulation and the amount of money saved by avoided losses. The mixing of hot and cold water in stratified tanks could also be significant, and can be minimised by using low inlet velocities. Over short storage timescales these will only constitute typically less than 5% of energy stored. Energy losses will affect the economic and environmental performance and have been factored into the analysis of Chapters 5 and 6.

7.2.3 Store Control Strategies

In Chapter 4, the store control strategy had the main objective of effectively using the heat from the CHP units to match this with the heat demand. If electrical load profiles had been available then this would have enhanced the model.

In Chapter 5 there was an obvious storage need since heat is produced only during half of the week and the power from the waste heat boilers is likely to be erratic and thus cannot be fed straight into the district heating system. The storage of water to produce consistently over a full week is likely to mean a very large volume need. The greater self-use of waste heat during winter months at the steelworks would likely free-up storage capacity which can then be used for peak demand shaving purposes.

In Chapter 6, the store was used to displace the use of expensive gas boilers and actually had the greatest benefit when the store capacity allowed electricity production to be targeted towards the higher price periods. However, it is important to note that these spot prices used in the analysis are not visible in advance or even in real time and therefore the targeting of high-price periods will be difficult in real life and there will be less of a revenue benefit from doing so.

7.2.4 Storage charging capacity

A limiting factor may be the power requirement of a store in order to decouple heat and electricity production. High power capacities are particularly difficult for phase change materials and chemical storage to achieve due to conductivity limits. Shaving a peak in demand by 15MW with a hot water store would require addition of almost 100 litres per second of hot water to a store, as well as the same amount of cold water leaving. An appropriate system would be required to ensure that a high inlet velocity does not cause excessive mixing in the hot water tank which could disrupt stratification and increase energy loss; multiple diffusers to slow down the water flow arranged symmetrically in the tank should be sufficient

There may be a comfortable range over which the plant can vary output with movement beyond this range being detrimental to performance. The combination of store with CHP unit has to meet demand at all times and smart operational strategies are required to eliminate the chance of the need for back-up boilers.

7.2.5 Locations of Storage

In Chapter 4, there are discussions of practicality for heat injection into the DH network; the highest suggested powers are $4MW_{th}$ due to the diameters of pipelines at various points in the network, as well as the limitations of space in boiler rooms (ARUP, 2012).

In Chapters 5 and 6, the need for a large number of pressure vessels to store hot water would likely prove problematic in terms of finding suitable host locations. Distribution of these tanks around the city would be one option but getting planning permission for their installation at many sites would likely be problematic.

Industry sites in the Lower Don Valley already host steam accumulators to store steam for their own processes. But there are significant periods during which this capacity is not used, for example Friday, Saturday and Sunday and during shutdown periods for maintenance work. During these periods a double-purpose pressure vessel could act as storage for DH water and thus provide storage capacity to the network. This would be a low up-front cost approach, if existing vessels can be adapted, and further pressure vessels could be added later if deemed beneficial.

7.2.6 Carbon Savings, Quality Index, Renewable Obligation Certificates

The carbon savings considered in the study are those associated with net import or export of electricity and the use of gas boilers and energy from waste or biomass. There are also embodied carbon emissions of the store itself; while they haven't been considered in this thesis, Martin and Thornley (2013) put these as high as 8 tonnes of carbon dioxide for a $74m^3$ store.

Key to the carbon savings from CHP and the use of heat pumps is the carbon intensity of grid electricity. To understand the sensitivity of carbon savings to this variable, different scenarios for grid carbon intensity were tested in Chapter 5. Predicting the carbon intensity is very difficult due to its dependence on future demand for electicity as well as the build-out of different types of generation and investigating the detail of this was beyond the scope of this work.

The Quality Index factors, designed to represent CHP performance actually showed very little change in the scenarios considered, for example as seen in Table 6-2. These factors were calculated to be very high for the energy from waste scheme, and changed little in the scenarios with heat storage added even though there were significant carbon benefits.

Also relevant is the finding that improved heat utilisation from the CHP reduces the Renewable Obligation Certificate income even though the efficiency of renewable energy use (from a heat andpower perspective) actually increases as shown in Figure 5-30. Also shown in that figure is the near irrelevance of the EU-ETS for achieving lower carbon outcomes.

8 CONCLUSIONS

Energy storage is a current research priority for many reasons including the increasing use of intermittent renewable energy, the objective of keeping energy costs down through the capture of energy that would otherwise go to waste, and to minimise the environmental impact of energy use. The United Kingdom is at a particularly important time when its ageing energy infrastructure is in need of renewal. The research within this thesis demonstrates effective approaches to energy storage and infrastructure that can be used to transform the UK's energy systems.

The literature review in Chapter 2 explored applications for heat storage, the operation of district heating systems and heat-intensive industry, as well as covering an extensive range of thermal energy storage technologies concluding that:

- sites of electricity generation and industrial activity have opportunities for heat recovery with thermal storage providing a means to means to manage that heat. Strategic planning is required to successfully use that heat through district heating;

- heat pumps driven by electricity are increasingly being used to provide heat for buildings with a need for heat storage to meet fluctuating demands as well as to move electricity use to off peak periods. Emerging examples of heat pumps used for district heating also provide opportunity for use of heat storage;

- heat storage is already used in a wide range of applications from domestic hot water storage to steam accumulators or molten salt technologies for high temperature and high pressure applications such as solar concentrating power plants;

- hot water storage remains the dominant heat storage medium for district heating with the advantages of being low cost with high specific heat capacity. It is non-corrosive, non-polluting and is easily circulated in heating systems and heating networks. Thermal oil and ceramics or gravel can be used to store heat at high temperatures at which water is either in the form of steam meaning low energy storage density or needs to be held under high pressure to prevent the water turning to steam. The additional costs of reinforcing storage vessels and distribution systems can be prohibitive;

- most thermal energy storage technologies remain in the research and development stages since they are too high in cost, they degrade over time, they are corrosive or other such problems. Phase change materials and chemical storage technologies were reviewed in detail for possible applications to the case studies in this thesis. The transfer of heat to and from phase change materials is made difficult by generally poor thermal conductivity. There are also problems over higher costs per unit of material, over thermal expansion during phase change, and the corrosive nature of some materials.

The research work described in Chapter 4 modelling thermal energy storage to accompany a new CHP at a university campus using the University of Sheffield as a case study to explore possible interventions concluded that:

- networking of buildings reduces significantly the peak heating capacity required. For the case study concerning 33 buildings the diversity factor was 45.4% meaning the collective load was less than half of the sum of individual peak loads. This ‘diversity factor’ is poorly documented for buildings in the UK and therefore the findings on diversity factors should prove a valuable research output. Where heat storage or boilers serve a network of customers then the peak heating capacity is reduced by this diversity factor meaning reduced capital and operational costs can be achieved;

- strategic placement of heat storage on a network running through the campus could alleviate bottlenecks in existing pipework allowing for an increase in network resilience and or capacity of the heat network. The use of heat storage in this way could also mean the optimal use of additional infrastructure for heating and cooling to be installed by the University;

- The University plans to introduce a combined heat and power (CHP) engine to achieve carbon footprint reduction and the addition of heat storage can allow the engine to run more continuously, hence increasing the carbon saving and reducing the amount of maintenance required;

- Addition of heat storage was shown to enhance the CHP engine’s financial benefit by allowing greater production of electricity at high price periods but the operational pattern of the engine depends critically on whether excess heat can be sold into the city-wide heat network. A thermal store was found to provide an estimated simple payback period of 17 to 25 years depending on the chosen engine configurations and capital costs as well as additional carbon savings of 16 to 19 tonnes of carbon dioxide per year. Providing benefits to the city-wide network as in Chapter 6 is more likely to bring financial and carbon saving.

The investigation of waste heat sources at a steelworks accompanied by district heating and biomass CHP system modelling described in Chapter 5 concluded that:

- there was significant potential for the recovery of waste heat from Sheffield Forgemasters to contribute to both the site’s own space heating demand as well as supplying heat for district heating;

- much of the waste heat is produced at a highly variable rate and for only part of the week. To make best use of recovered heat for district heating or re-use on site would require a large heat storage capacity. The exact optimal capacity depends on the capital investment required as well as the price for heat sold to district heating and is in the region of 500 m^3;

- that low temperature waste heat streams such as cooling water would need to be upgraded using high temperature heat or electricity to drive a heat pump. Under current grid emissions factors the carbon benefit of doing so is low and the economic benefit will depend on the price of electricity used for this purpose with various price scenarios for 2030 also tested;

- the best option for heat storage is the use of a hot water accumulator operating at the same temperatures as the new district heating network. The reason for this is the avoidance of inefficiencies and expenditure on heat exchangers as well as the advantage that the thermal store can serve the district heating network and benefit its operation even when the steelworks is not operational hence providing a better return on investment;

- heat recovery from Sheffield Forgemasters could save 1419 tonnes of CO_2 per year. The effective carbon price seen by industry will impact on the cost-effectiveness of the project. Future trajectories of CO_2 price consistent with the UK's climate change obligations would incentivise this project in line with the large carbon saving potential.

The expanded district heating model described in Chapter 6 considered Sheffield's existing city centre district heating system as well as the new district heating scheme in Sheffield's Lower Don Valley and the potential advantages of interconnection of the two schemes concluding that:

- the city-centre district heating network shows a correlation between CHP availability and the emissions factor for heat supplied through the network. The trade-off between heat and power production was also clearly derived from the data leading to more accurate modelling of the network operation;

- the existing city-centre scheme would gain significant increase in revenue and benefit by using thermal storage in order to reduce the use of fossil-fuel boilers for meeting peak demands and to increase the average revenue received for electricity sales. It was shown that the possible increase in revenue for electricity sales was much more significant a factor than reduced gas consumption;

- interconnection of the two district heating schemes would also result in a significant reduction of fossil fuel boiler usage since each of the CHP units would be able to cover some periods of outage at the other CHP plant where fossil fuel boilers would normally be required;

- interconnection of the two networks does significantly reduce the benefit seen from adding heat storage to the city-centre network;

- the pipes of the network themselves could be used as heat storage but this would be difficult to control the variations of temperature circulate in the network with the water itself and charging and discharging of a pipe are limited by the rate at which water can flow through the pipes which is limited for safety reasons.

In summary, through data analysis and modelling in this thesis it has been possible to draw some case study-specific conclusions as well as some with wider applicability. Those conclusions with wider applicability include:

- there are benefits from building a network since diversity factor gives a better utilisation of high capital expenditure heat sources. For policymakers interested in decarbonisation of heating supplies, this is likely to represent a means to maximise impact of low carbon heating investment;
- constructing a network between heat storages such as those seen in Chapter 4 and Chapter 6 case studies assists viability of the heat stores by enabling new means to deliver carbon and cost savings;
- the carbon savings achieved by CHPs and heat pumps has also been shown to be strongly dependent on the carbon intensity of grid electricity, hence it is important to understand the impact of various grid decarbonisation scenarios when assessing interventions.
- some of the incentives around Renewable Obligation Certificates were found actually to disincentivise greater heat use from the CHPs. This highlights the importance of viewing heat and power policy in a holistic manner in order to achieve the more efficient and lower-carbon outcomes. Also shows was seemingly small impacts of the Quality Index metric as well as the ineffectiveness of the EU ETS at current prices.

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10 APPENDIX

10.1 Publication, Presentation and Prize List

Journal Publication

Raine, R.D., Sharifi, V.N., Swithenbank, J. 2014, Optimisation of combined heat and power production for buildings using heat storage. Energy Conversion and Management, 87, 164-174.

Conference Papers, Presentations, Posters

BBC Radio 5 Live Energy Day, presentation and demonstration of research, 5th September 2013, MediaCityUK, Salford, UK.

Raine, R.D., Sharifi, V.N., Swithenbank, J., Sheffield's Low Carbon Heat Network and Its Energy Storage Potential, poster presentation (reproduced below), University of Sheffield Engineering Symposium, 24th June 2014, Sheffield, UK.

Raine, R.D., Sharifi, V.N., Swithenbank, J., Hinchcliffe, V., Segrott, A. 2014, Sustainable Steel City: Heat Storage and Industrial Heat Recovery For A District Heating Network. Oral presentation and written paper, 14th International Symposium on District Heating and Cooling, 7th September 2014, Stockholm, Sweden.

Raine, R.D., Low Carbon Heat Networks and Their Energy Storage Potential, presentation to students of the Energy Storage Centre for Doctoral Training, University of Sheffield, 20th November 2014.

Raine, R.D., Low Carbon Heat Networks and Their Energy Storage Potential, presentation to students of the MSc in Environmental and Energy Engineering, University of Sheffield, 13th March 2015.

Raine, R.D., Sheffield's Low Carbon Heat Network and Its Energy Storage Potential, Postrgraduate Research Conference, Department of Chemical and Biological Engineering, University of Sheffield, 10th June 2015, Sheffield, UK.

Raine, R.D., Sharifi, V.N., Swithenbank, J., Modelling industrial waste heat recovery from a steelworks with heat storage to supply low carbon heat for district heating. Oral presentation and written paper, Sustainable Thermal Energy Management (SusTEM) Conference, 7th July 2015, Newcastle, UK.

Prizes

Energy Institute Foxwell Memorial Prize 2014.

University of Sheffield Engineering Symposium 2nd Place Poster Prize, 25th June 2014.

Figure 10-1: Energy Secretary Ed Davey visits research demonstration stall during BBC Energy Day, September 2013.

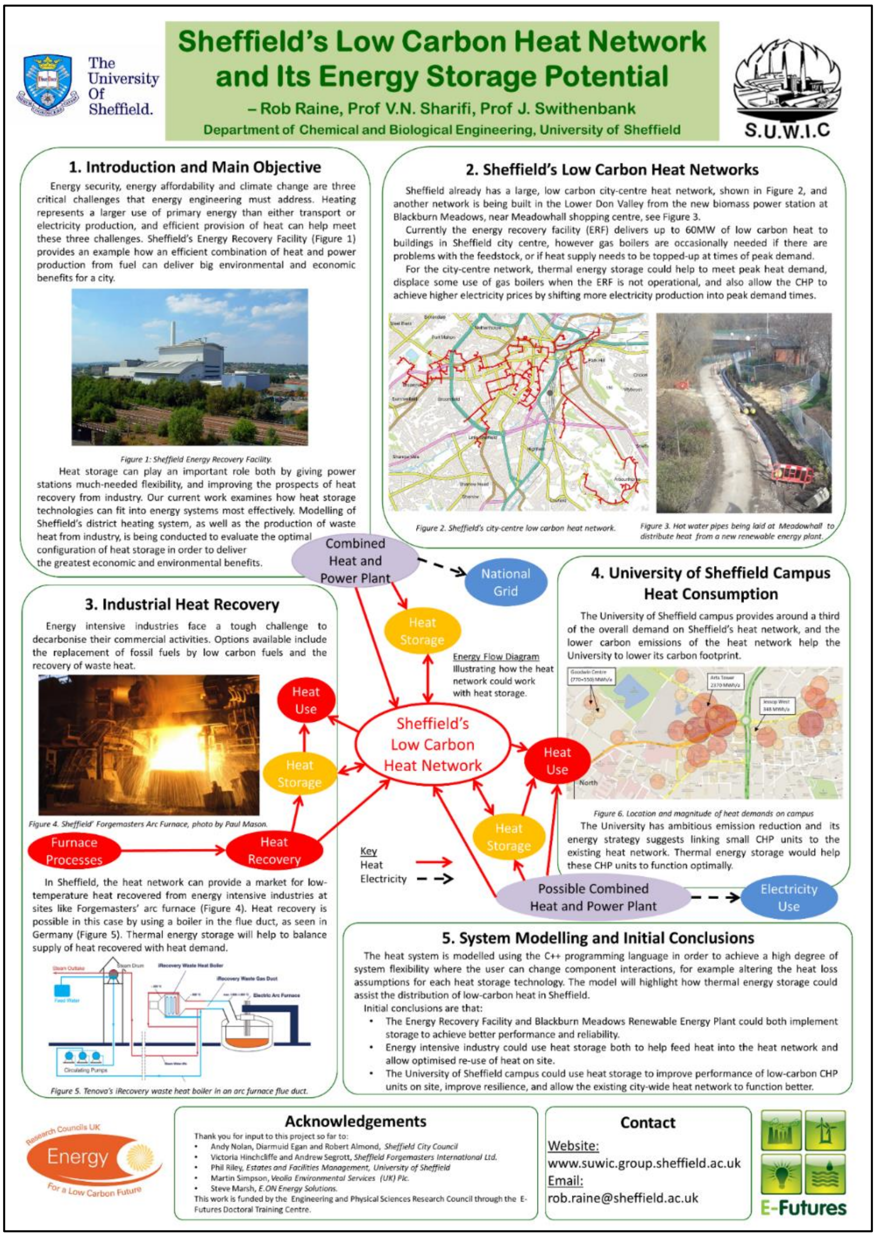

Figure 10-2: Poster presented at the University of Sheffield Engineering Symposium, June 2014.

10.2 University of Sheffield Building Details

Table 10-1: Data properties for the full datasets.

Buildings with a reading for every half-hour for May '12 to November '13. Annual demand assessed from July '12 to June '13

Building Code	Building Name	Building Function	Zone	Reading Resolution	Jul '12 to Jun '13 Demand (MWh/a)	Comments
2029	Biology Block (Denny)	Research	6	OK	2935	.
2030	Chemistry Beaumont	Research/ Lectures	6	Low	4088	Distinct winter heating period.
2032	Edwardian Building	Research	6	OK	1610	Late June to end Sept 2013 data poor.
2034	Hicks	Research/ Lectures	5	Good	1653	Off in Summer, on in September.
2035	Western Bank	Library	6	Good	598	Off in Summer, on in September.
2037	Old Refractory (Amy J Annexe)		10	Poor	137	
2039	Old Students Union/Graves	General	5		0.1	Very little use.
2041	West Wing/ North Wing		6	Good	1586	Anomalous weeks in late November 2012, and mid Oct 2013. Load seems almost double in 2013 winter
2043	Bursars Admin Building (Addison)	Admin	6	Good	406	
2044	Porters Lodge and Firth Hall	Admin/ General	5		277	Missing data from late September 2012 to end of 2012.
2046	Geography Building	General	6	Good	587	Distinct heating season.
2047	Octagon Centre	Events	5	Good	535	
2054	Bartolome House	General	6	Good	747	Summer switch off is clear.
2076	Elmfield	General	1	Good	586	Summer switch off is clear.
2136	Computing Services	Offices	5	Good	109	
2169	Admin/Showers Goodwin		1	Low	130	Low demand levels, quite consistent.
2170	Psychology	General	2	Good	667	Step down in heat use significantly more in Summer 2013 than 2012.
2173	Cofield Pool	Swimming Pool	1	Good	1200	Significant year-round heat load.
2320	Central Annexe (Print Services/ APS)	General/ Research	6	Good	196	End of 2012, intra-day variability significant, then

						becomes less variable in mid-January.
2352	Old Students Union Extension	General	5	Good	349	End of September switched on.
2516	Quadrangle (Florey Building)	Research	6	Poor	158	
2523	Information Commons	Library	5	OK/Poor	634	Clear heating season.
2524	ICOSS		8	OK	513	Clear heating season, week of missing demand in January.
2542	Bioincubator	Research	8	OK/Poor	363	
2549	North Campus	Research	9	OK/Poor	1749	Significant base load
2550	North Campus Stage 2	Research	9	Good	1066	Clear Heating Season
2556	Psychology Annexe (IWP)	General	2	OK	104	
2557	Chemistry North	Research	6	Poor	397	
2559	Jessop West	General	8	Good	425	
2561	Jessop Building		8	Good	229	Mid January shows a step up in the daily minima of demand.
2566	Dainton		6	Poor	233	Poor resolution of data
			TOTAL (31 buildings):		**24,267**	**MWh/year**

Table 10-2: Building records with partial data.

Buildings with missing readings. * = data taken from University's 2012 bills.

Building Code	Building Name	Building Function	Zone	Data Quality	Estimated Demand (MWh/a)	Comments
Two buildings have complete records during July 2012 to June 2013 which is studied in greater detail.						
2067	North Campus	Research	9	Poor	1594	Gap 6/6/12 to 13/6/12
2535	Shearwood Rd		4		908	Missing data from September 2013
Other buildings have data anomalies and/or figures missing from the 12 months studied in greater detail.						
2026	Amy Johnson	Research	10	Good	261	Gap in readings 24/5/13-24/7/13.
2027	Broad Lane Block* (Applied Science)	Research	10	Poor	1560*	Readings 10/6/13-19/9/13, annual estimate from different University figures for 2012.
2028	Arts Tower	Mixed	6	Good	2311	Roughly 12 months of coverage overall. Big problems with metering through time.
2031	Chemistry North – 1212		6	OK	1205*	Reads OK but demand missing for 2012/13. Estimates used from University's 2012 figures.
2033	Foundry Heating/Materials		10	Poor	105*	Reads OK but demand only appears on 16/10/13.
2036	Hadfield Building (DHW*)		10	Poor	12*	Anomalous pattern of wrongly low demand, no demand after May '13, no readings after Nov '13.

2038	St George's Church	Lectures	8	Good	549*	Decent readings start of 31/7/13.
2045	Division of Education	General	5	Good	617*	Good half-hour data for October/November 2013
2168	Goodwin Gym	Leisure	1	Good	374*	Good data from September 2013 onwards
2294	Portobello Centre		10	Poor	375*	Very little demand registered in the half-hour readings.
2322	Biology Block Extension (Perak)	Research	6	OK/ Poor	419*	OK data for October/November 2012, poor data otherwise.
2355	Brunswick St		5		65*	Ok data from 7th October 2013.
2380	Hadfield Tower (htg)		10	No data	361*	No data. This is from a billing estimate, but higher than the ARUP (2012) number (around 260 MWh/annum)
2381	Mappin Building	Research/ Admin/ Lectures	10	Good	3000	Good data from end of September 2012 until mid June 2013, missing week or two at start of April.
2515	Print Services/ Plant Sciences	Research	6		468*	OK data from August 2013 but poor resolution of readings.
		Completely missing from 30-minute series:				
2572	Chelsi Building	Research	10		168*	
2040	University House	Admin	5		1989*	
Total of 19 buildings with some missing data:					**16,341**	**MWh/year**

Overall the demand for 2012/13 is 40,608 MWh of which 24,267 MWh (59.8%) is accounted for in full half-hour records for 31 buildings over 18 months. 26,769 MWh is accounted for in full records from July 2012 to June 2013, constituting an estimated 65.9% of the total. For zone 6, 13,541 MWh out of 17,944 MWh is available for the July 2012 to June 2013 period.

10.3 Run Period Priority Allocation Algorithm

When simulating the gas fired CHP engine in heat load follow mode for Chpater 4, the load dispatch schedule is determined by formulae in Microsoft Excel. The calculations are carried out on a day-by-day basis with no forward looking strategy that will affect where the store finishes the end of the day (unlike the model developed for Chapter 5).

- Half-hourly heat demands (perfect prediction) are loaded into the spreadsheet.
- The average demand for the day is calculated.
- A pre-determined sequence gives priority regarding times when the CHP is on. After the first period, consecutive periods are adjacent to ones where the CHP is on. The sequence of numbered half-hour periods begins with 16:00-19:00 pm (when distribution and transmission use of system costs are highest) and the proceeds in this model to successive periods through the day time periods with higher demand (between 7am and 4pm) then those with lower demand (from 7pm until midnight) and then finally from 7am back until midnight to complete the day.

Table 10-3: Run period priority in the algorithm of Chapter 4.

Priority	Time	Priority	Time	Priority	Time	Priority	Time	Priority	Time	Priority	Time
1	16:00	9	14:30	17	10:30	25	19:00	33	23:00	41	3:30
2	16:30	10	14:00	18	10:00	26	19:30	34	23:30	42	3:00
3	17:00	11	13:30	19	9:30	27	20:00	35	6:30	43	2:30
4	17:30	12	13:00	20	9:00	28	20:30	36	6:00	44	2:00
5	18:00	13	12:30	21	8:30	29	21:00	37	5:30	45	1:30
6	18:30	14	12:00	22	8:00	30	21:30	38	5:00	46	1:00
7	15:30	15	11:30	23	7:30	31	22:00	39	4:30	47	00:30
8	15:00	16	11:00	24	7:00	32	22:30	40	4:00	48	00:00

- The CHP is modelled to be on during a period *i* provided that the period *i* falls before the n+1th member of the sequence above where

$$n \times Q_{CHP} \leq \sum_{i}^{48} Q_{DH}$$

  Such that the CHP energy output does not exceed the DH demand for the day.

- Where there is more than one CHP unit, the allocation runs for one unit until it runs for the whole day and then repeats for the second unit with the same priority sequence until the correct.

10.4 ERF Operational Statistics

Table 10-4 presents performance statistics from the Sheffield Energy Recovery Facility.

Table 10-4: Annual performance figures for Sheffield Energy Recovery Facility.
Source: UKWIN (2015).

Year	2007	2008	2009	2010	2011	2012
Operating hours (h)	7,182	7,018.4	7951.1	7556.53	7567.5	8010.0
Availability (%)	82.0	79.9	90.8	86.3	86.4	91.2
Tonnes of waste	196,505	183,070	219,976	202,814	207,000	226,991
Electricity produced (MWh)	106,080	89,737	115,624.95	106,564	110,556	114,583
Electricity exported (MWh)	91,870	77,543	100,066.45	92,452	95,378	98,549.9
Energy to DH (MWh)	86,222	102,654	97,292.4	109,073.82	98,129.74	132,096.15
DH Sales	109,086	114,901		129,464	95,938.95	110,913
% DH from ERF	79	89		84.3		
Notes			1027 MWh of gas in ERF		More energy to DH than sold	

10.5 Computer Algorithms

The computer algorithm comes in two parts, one to read heat demand figures and waste heat production patterns then calculate the use of CHP and gas boilers. The second part then takes that scenario and uses various amounts of storage and uses the store to achieve the objectives as described in Section 5.4.8.

10.5.1 Base Case Model

```
//BCA1.cc Prints base heat source pattern (no store)
// use: ./BCA1 1 85 95 17 for sc 1 in 17 demand steps 89-95 GWh
#include <iostream>
#include <cmath>
#include <fstream>
using namespace std;
class HeatSource{
public:
  float DH1[7][48],DH2[7][48],DH3[7][48]; //time+rate of DH prod, day1= Sat
  float Op[52]; //operational weeks
  float WeeklyDHProd,WeeklyDHProd1,WeeklyDHProd2,WeeklyDHProd3,WeeklyStProd,Prod;
```

```
  void ReadInProd(int Sc);
};
class MktVary{
public:
  float Mkt[5][6];//Market:Index,Scen,DHDemand,EafDH,EafSt,GasDH,HPOut
  void ReadInMarket();
  float EafDH,EafSt,GasDH,HPOut;
};

void SumElements748(float matrixName[7][48],float &Sum);
void SumElements52(float ArrayName[52],float &Sum2);

int main(int argc,char* argv[]) //Command line inputs,scenario only
{
  HeatSource SFIL;//Forgemasters
  float HNDem,GasHeatSold,GasHeat,CHPHeatSold,LIWH,CHPHeat,CHPMax,CHPMin;
  CHPMax=25.0;CHPMin=1.0;
  float AnnualHNDemand=0.0;
  int ScPrint,DemNo;
  float Div1,Div2,Div3, Div5,DemMin,DemMax,Demand;
  ifstream fin,fin2;
    if(argc>1){sscanf(argv[1],"%d",&ScPrint);}else{cout<<"Scenario ";cin>>ScPrint;}
    if(argc>2){sscanf(argv[2],"%f",&DemMin);}else{cout<<"Minimum demand ";cin>>DemMin;}//GWh
    if(argc>3){sscanf(argv[3],"%f",&DemMax);}else{cout<<"Maximum demand ";cin>>DemMax;}
    if(argc>4){sscanf(argv[4],"%d",&DemNo);}else{cout<<"Number of demands ";cin>>DemNo;}
    if(ScPrint>5)cout<<"ERROR!"<<endl;

    MktVary Sc;//Index,Scen,DHDemand,EafDH,EafSt,GasDH,HPOut
    Sc.ReadInMarket();SFIL.ReadInProd(ScPrint);//need to know market

    cout<<"Annual Demand: ";
    for (int i=0;i<DemNo&&DemNo>1;i++)
      cout<<static_cast<float>(DemMin+i*(DemMax-DemMin)/(DemNo-1))<<" GWh/a ";
    if(DemNo==1)cout<<DemMin<<" GWh/a ";
    cout<<endl;
    cout<<"Waste Heat Contributions:"<<endl;
cout<<"EAF DH: "<<Sc.Mkt[ScPrint-1][2]<<endl;cout<<"EAF Steam: "<<Sc.Mkt[ScPrint-1][3]<<endl;
cout<<"Gas DH: "<<Sc.Mkt[ScPrint-1][4]<<endl;cout<<"Cooling DH:"<<Sc.Mkt[ScPrint-1][5]<<endl;
    //Div is sum of elements
    SumElements748(SFIL.DH1,Div1);SumElements748(SFIL.DH2,Div2);//2nd pattern
    SumElements748(SFIL.DH3,Div3);SumElements52(SFIL.Op,Div5);

    //Set Scenario Parameters
    Sc.EafDH=Sc.Mkt[ScPrint-1][2];Sc.EafSt=Sc.Mkt[ScPrint-1][3];
    Sc.GasDH=Sc.Mkt[ScPrint-1][4];Sc.HPOut=Sc.Mkt[ScPrint-1][5];

    for (int A=0;A<DemNo;A++)
    {if(DemNo>1)Demand=static_cast<float>(DemMin+A*(DemMax-DemMin)/(DemNo-1));
      else Demand=DemMin;
    GasHeatSold=0;GasHeat=0;CHPHeatSold=0;CHPHeat=0;AnnualHNDemand=0;

    //need Div5 for each scenario if >1 input, separate terms below w if functions
    //if there's LIWH, then depends on priority of heat use, e.g. primary first

    SFIL.WeeklyDHProd1=static_cast<float>(Sc.EafDH/Div5);//pattern1 heat production
    SFIL.WeeklyDHProd2=static_cast<float>(Sc.GasDH/Div5);//pattern2
    SFIL.WeeklyDHProd3=static_cast<float>(Sc.HPOut/Div5);//pattern3
    SFIL.WeeklyStProd=static_cast<float>(Sc.EafSt/Div5);

    //NO LONGER SPECIFIED
    float Norm1=2*SFIL.WeeklyDHProd1/Div1; //*element for hourly production
    float Norm2=2*SFIL.WeeklyDHProd2/Div2;
    float Norm3=2*SFIL.WeeklyDHProd3/Div3;

  ofstream fout;

if(A==0)fout.open("Series0.dat");if(A==1)fout.open("Series1.dat");if(A==2)fout.open("Series2.dat");if(A==3)fout.open("Series3.dat");if(A==
4)fout.open("Series4.dat");if(A==5)fout.open("Series5.dat");if(A==6)fout.open("Series6.dat");if(A==7)fout.open("Series7.dat");if(A==8)fout.
open("Series8.dat");if(A==9)fout.open("Series9.dat");if(A==10)fout.open("Series10.dat");if(A==11)fout.open("Series11.dat");if(A==12)fout.
open("Series12.dat");if(A==13)fout.open("Series13.dat");if(A==14)fout.open("Series14.dat");if(A==15)fout.open("Series15.dat");if(A==16)fo
ut.open("Series16.dat");if(A==17)fout.open("Series17.dat");if(A==18)fout.open("Series18.dat");if(A==19)fout.open("Series19.dat");if(A==20
)fout.open("Series20.dat");if(A>20)cout<<"TOO MANY!"<<endl;

  fin.open("Demand120.dat");fin2.open("Avail1.dat");

  //float StoredTemp;
for(int time=0;time<17472;time++)//time in half-hours 0:17472, 52 weeks.
  { int n,l,m,Av;//Half hour No, Week No, Day of week 0=Sat
      n=time%48;l=(time/336);m=(time/48)-l*7;
```

```
  //INSTANTANEOUS DEMANDS
    SFIL.Prod=SFIL.DH1[m][n]*Norm1*SFIL.Op[l];
    SFIL.Prod+=SFIL.DH2[m][n]*Norm2*SFIL.Op[l];
    SFIL.Prod+=SFIL.DH3[m][n]*Norm3*SFIL.Op[l];
    fin>>HNDem;
    fin2>>Av;
    HNDem=HNDem*Demand/120;GasHeat=0;CHPHeat=0;LIWH=0;

    //Decision of heat sources
    if(HNDem<CHPMin&&HNDem-SFIL.Prod>0){CHPHeat=0;GasHeat=HNDem-SFIL.Prod;LIWH=0;}
    if(HNDem<CHPMin&&HNDem-SFIL.Prod<0){CHPHeat=0;GasHeat=0;LIWH=SFIL.Prod-HNDem;}

    if(Av==1)
                {if(HNDem>CHPMin&&HNDem-SFIL.Prod<CHPMin)
                   {CHPHeat=CHPMin;GasHeat=0;LIWH=CHPMin-(HNDem-SFIL.Prod);}
                 if(HNDem>CHPMin&&HNDem-SFIL.Prod>CHPMin&&HNDem-SFIL.Prod<CHPMax)
                   {CHPHeat=HNDem-SFIL.Prod;GasHeat=0;LIWH=0;}
                 if(HNDem>CHPMin&&HNDem-SFIL.Prod>CHPMin&&HNDem-SFIL.Prod>CHPMax)
                   {CHPHeat=CHPMax;GasHeat=HNDem-SFIL.Prod-CHPMax;LIWH=0;}
                }
    if(Av==0||Av==2)
                { if(HNDem-SFIL.Prod<CHPMin)
                   {CHPHeat=0;GasHeat=CHPMin;LIWH=CHPMin-(HNDem-SFIL.Prod);}
                 else {CHPHeat=0;GasHeat=HNDem-SFIL.Prod;LIWH=0;}
                }

   AnnualHNDemand+=HNDem/2;
   fout<<0.5*time<<"\t"<<SFIL.Prod<<"\t"<<HNDem<<"\t"<<CHPHeat<<"\t"<<GasHeat<<"\t"<<LIWH<<endl;
  }//time looping

 cout<<"HN Demand: "<<AnnualHNDemand<<endl;
 fout.close();fin.close();fin2.close();
  }//A-loop
 return 0;
}

void HeatSource::ReadInProd(int Sc)//Defines Heat Source
{
 ifstream finA,finB,finC;//Read in the ON times,
 //distinguishes patterns
 finB.open("SFILProdB.dat");
 for(int i=0;i<7;i++){for(int j=0;j<48;j++)finB>>DH2[i][j];};
 finC.open("SFILProdC.dat");
 for(int i=0;i<7;i++){for(int j=0;j<48;j++)finC>>DH3[i][j];};
 finA.open("SFILProdA.dat");
 for(int i=0;i<7;i++){for(int j=0;j<48;j++)finA>>DH1[i][j];};

 finA.close();finB.close();finC.close();
 ifstream fin2;//Read in the Operational Weeks
 fin2.open("SFILOpWks.dat");
 for(int i=0;i<52;i++)fin2>>Op[i];
 fin2.close(); //The heat source is now defined
}

void MktVary::ReadInMarket()
 { ifstream fin6;
  fin6.open("ScInputs.dat");
  for(int i=0;i<5;i++){for(int j=0;j<6;j++)fin6>>Mkt[i][j];};
  fin6.close();
 }

void SumElements748(float matrixName[7][48],float &Sum)
{ Sum=0.0;
 for(int m=0;m<7;m++){for(int n=0;n<48;n++)Sum+=matrixName[m][n];}
}

void SumElements52(float ArrayName[52],float &Sum2)
{ Sum2=0.0;
 for(int n=0;n<52;n++)Sum2+=ArrayName[n];
}
```

10.5.2 Heat Production Variability files

SFILProdA.dat (representing variability of district heating production from EAF flue gases)

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2

3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2

3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2

3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 1 2 3 2 3 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

SFILProdB.dat (representing variability of district heating production from gas furnace flue gases)

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 2 2 2 2 1 1 1 1 0 0 0 0 0 0

SFILProdC.dat (representing variability of district heating production from EAF cooling water)

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3

4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3

4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3

4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 2 3 4 4 3 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

10.5.3 Heat Store Algorithm

```
//SPA10.cc
//use:./SPA10 0 30 3 1 354 >MultiFileSc1v2 uses 9 Caps 0-30, prints day 354
//number 1 is from the ./BC2 (number of demand scenarios)
#include <iostream>
#include <cmath>
#include <fstream>
using std::cin;using std::cout;using std::endl;using std::ifstream;using std::ofstream;
class HeatStore{
public:
  float Stored,Cap;//cap = capacity
  float CR[48];//charge rate
};
class HighOrLow{
public:
  int t;
  float Price;
};

int main(int argc,char* argv[])
{
  HeatStore Tank;
  float AnnIWHLost,AnnIWHCaught,AnnIWHSold,AnnLoss;//IWH=Industry Waste Heat
  float AnnDem,AnnCHPSales,AnnCHPElecSales,AnnGasSales,StMin,StMax;
  int AnnSwitchCount,L,J,StNo,DemNo;
  HighOrLow Hi,Lo;
  if(argc>1){sscanf(argv[1],"%f",&StMin);}else{cout<<"Minimum Store Value ";cin>>StMin;}
  if(argc>2){sscanf(argv[2],"%f",&StMax);}else{cout<<"Maximum Store Value ";cin>>StMax;}
  if(argc>3){sscanf(argv[3],"%d",&StNo);}else{cout<<"Number of Store Values ";cin>>StNo;}
```

```
  if(argc>4){sscanf(argv[4],"%d",&DemNo);}else{cout<<"Number of Demand Values ";cin>>DemNo;}

  float StoreYearStart,StoreYearEnd,StoreDayStart,SDE,SDETemp;//SDE=StDayEnd
  float SDEMin,SDEMax,CHPMax,CHPMin,CHPElecCap,CHPZ,CHPDayEnd,CRMin;
  float IWHCaught,IWHSold,GasHeatSales,CHPHeatSales,CHPElecSales,ElecRevenue,ROCRev,QI;
  float Q[48][6],DAQ[48][6];//Power inputs: t(h),IWHPr,HNDe,CHPHe,GasSa,LIWH
  float StVary[48],StVaryTemp[48],CRTemp[48],LostIWH[48],Price[48];
  int Av[48];//AVAILABILITY 0-unplanned out, 1-available, 2-planned out
  float LIWHLater[48],GasLater[48],CHPEarlier[48],CHPLater[48],HL[48],HLTemp[48];//heat loss
  float HL_0,HL_c;//Heat Loss Power, HL[k]=HL_0*HWTank.StorCap+HL_c*StoredVary[k]
  float IntLostIWH,IntDem,SumCRT,HeadRoom,FootRoom;
  float PrimaryEnergyInput,TotalAnnualHeat,SumDAL,SumDACMin,SumDACMax,SumDAG;
  float ROCValue=45.0;//£/ROC, 1.9 ROCs for biomass CHP
  float Zero=0.00001;//Negligible increment to distinguish numbers that might be very similar
  bool VoidLoop,VoidLoop2,P3A,P3B,P3C,P4,P5a,P5b,P6,P7,P8;
  ifstream fin,fin2,fin7;
  ofstream fout;
  //active parts
  P3A=1;P3B=1;P3C=1;P4=1;P5a=1;P5b=1;P6=1;P7=1;P8=1;

  for(int B=0;B<DemNo;B++)//repeats different demand levels
  {
  for(int A=0;A<StNo;A++)//repeats for different store capacities
  {

if(B==0)fin.open("Series0.dat");if(B==1)fin.open("Series1.dat");if(B==2)fin.open("Series2.dat");if(B==3)fin.open("Series3.dat");if(B==4)fin.
open("Series4.dat");if(B==5)fin.open("Series5.dat");if(B==6)fin.open("Series6.dat");if(B==7)fin.open("Series7.dat");if(B==8)fin.open("Series
8.dat");if(B==9)fin.open("Series9.dat");if(B==10)fin.open("Series10.dat");if(B==11)fin.open("Series11.dat");if(B==12)fin.open("Series12.dat
");if(B==13)fin.open("Series13.dat");if(B==14)fin.open("Series14.dat");if(B==15)fin.open("Series15.dat");if(B==16)fin.open("Series16.dat");
if(B==17)fin.open("Series17.dat");if(B==18)fin.open("Series18.dat");if(B==19)fin.open("Series19.dat");if(B>19)cout<<"Too
Many!"<<endl;//up to 20 demand levels

  StoreYearStart=0;StoreYearEnd=0;StoreDayStart=StoreYearStart;SDE=0;SDETemp=0;
  if(StNo>1)Tank.Cap=static_cast<float>(StMin+A*(StMax-StMin)/(StNo-1));else Tank.Cap=StMin;
  //HEAT LOSS: HL_0*Cap+HL_c*Stored kW,  no store-no loss
  HL_0=0.001;HL_c=0.0005;

  //Initialise Annual Parameters
  AnnIWHCaught=0;AnnIWHLost=0;AnnIWHSold=0;AnnDem=0;
  AnnCHPSales=0;AnnGasSales=0;AnnCHPElecSales=0;
  Tank.Stored=StoreDayStart;ElecRevenue=0;AnnSwitchCount=0;AnnLoss=0;
  CHPMax=25;CHPMin=1;CHPElecCap=31;CHPZ=6;//CHP Parameters
  CHPDayEnd=CHPMin;//CHPDayEnd reset at end of each day to determine any switches on/off
  fin2.open("Avail1.dat");fin7.open("SpotData.dat");fout.open("NewSeries.dat");
  //set day ahead values ready for first day to use:
  for(int n=0;n<48;n++){for(int j=0;j<6;j++)fin>>DAQ[n][j];}

for(int day=1;day<365;day++)//StoreDayStart value set @ end of previous day
{
  GasHeatSales=0;CHPHeatSales=0;CHPElecSales=0;IWHCaught=0;IWHSold=0;
  IntLostIWH=0;IntDem=0;CHPHeatSales=0;
  //set values of arrays for day and heat losses
  for(int n=0;n<48;n++)
```

```
  { Tank.CR[n]=0;CRTemp[n]=0;GasLater[n]=0;LIWHLater[n]=0;
   StVary[n]=StoreDayStart;StVaryTemp[n]=StVary[n];
   //heat losses for tank will be set later
   HL[n]=0;HLTemp[n]=0;
   for(int j=0;j<6;j++)Q[n][j]=DAQ[n][j];//order:t(h),IWHPr,HNDe,CHPHe,GasSa,LIWH
   LostIWH[n]=Q[n][5];
   if(day<364){for(int j=0;j<6;j++){fin>>DAQ[n][j];};}//get day ahead powers from file
   fin2>>Av[n];//know availability of CHP
   fin7>>Price[n];//for economic optimisation
  }

 //PART 1,2,3: uncoordinated action at one time of day, each affect StoreDayEnd
 for(int k=0;Tank.Cap>Zero&&k<48;k++)//store present
  {
   //1. Set heat losses
   HL[k]=HL_0*Tank.Cap+HL_c*StVary[k];
   if(k<47){StVary[k+1]=StVary[k]+0.5*(Tank.CR[k]-HL[k]);StVaryTemp[k+1]=StVary[k+1];}
   else {SDE=StVary[47]+0.5*(Tank.CR[47]-HL[47]);SDETemp=SDE;}

   //2. Make up for heat losses if tank fully empty
   CRMin=(-StVary[k]/0.5)+HL[k];
   //check if LIWH/higher CHP to achieve CRMin and cover gas falls in the CHP output range
   //else gas boilers will achieve the minimum charge rate.
   if(Tank.CR[k]<CRMin-Zero)
    if(LostIWH[k]>Zero)
            {if(LostIWH[k]<CRMin-Tank.CR[k]){Tank.CR[k]+=LostIWH[k];LostIWH[k]=0;}
             else {LostIWH[k]-=CRMin-Tank.CR[k];Tank.CR[k]=CRMin;}
            }
   if(Tank.CR[k]<CRMin-Zero)
    {if(Av[k]==1&&Q[k][3]+Q[k][4]+(CRMin-Tank.CR[k])<CHPMax&&Q[k][3]+Q[k][4]+(CRMin-Tank.CR[k])>CHPMin)
             {Q[k][3]+=(CRMin-Tank.CR[k])+Q[k][4];Tank.CR[k]=CRMin;Q[k][4]=0;}
            else {Q[k][4]+=(CRMin-Tank.CR[k]);Tank.CR[k]=CRMin;}
    }

   //3A. Raise CHP to its minimum level: d(Q_CHP+Q_G)-dCR=0 occurs e.g. if(Dem<CHPMin)
   if(P3A==1&&Av[k]==1&&Q[k][3]+Zero<CHPMin&&StVary[k]+0.5*(Tank.CR[k]-HL[k]+CHPMin-Q[k][4])<Tank.Cap)
    { Q[k][3]=CHPMin;Tank.CR[k]+=CHPMin;
            if(Q[k][4]>Zero){Tank.CR[k]-=Q[k][4];Q[k][4]=0;}
            if(LostIWH[k]>Zero)LostIWH[k]+=CHPMin;//added
    }
   //3B. Add lostIWH to store if there is room
   if(P3B==1)
    {if(LostIWH[k]>Zero&&(StVary[k]+0.5*(Tank.CR[k]-HL[k]+LostIWH[k])<Tank.Cap))
             {Tank.CR[k]+=LostIWH[k];LostIWH[k]=0.0;}
            else if(LostIWH[k]>Zero&&StVary[k]+0.5*(Tank.CR[k]-HL[k])+Zero<Tank.Cap)
             {Tank.CR[k]+=2.0*(Tank.Cap-(StVary[k]+0.5*(Tank.CR[k]-HL[k])));
              LostIWH[k]=Q[k][1]+Q[k][3]+Q[k][4]-Tank.CR[k]-Q[k][2];
             }
    }
   //3C. Displace gas use where possible
   if(P3C==1)
    {if(Q[k][4]>Zero&&(StVary[k]+0.5*(Tank.CR[k]-HL[k]-Q[k][4])>Zero))
             {Tank.CR[k]-=Q[k][4];Q[k][4]=0.0;}
```

```
                    else if(Q[k][4]>Zero&&StVary[k]+0.5*(Tank.CR[k]-HL[k])>Zero)
                     if(StVary[k]+0.5*(Tank.CR[k]-HL[k]-Q[k][4])<-Zero)
                      {Tank.CR[k]-=2.0*StVary[k]+Tank.CR[k]-HL[k];
                       Q[k][4]=Q[k][2]+Tank.CR[k]+LostIWH[k]-Q[k][3]-Q[k][1];
                      }
   }
  //Correct the store level and losses through to end of day.
  for(int K=k;K<48;K++)
   { if(K<47){StVary[K+1]=StVary[K]+0.5*(Tank.CR[K]-HL[K]);
                     StVaryTemp[K+1]=StVary[K+1];HL[K+1]=HL_0*Tank.Cap+HL_c*StVary[K+1];}
                    if(K==47){SDE=StVary[47]+0.5*(Tank.CR[47]-HL[47]);SDETemp=SDE;}
   }
 }

float HighDAHL=0;//heat losses if store on high trajectory from SDEMax
float LowDAHL=0;//heat losses if store on high trajectory from SDEMin
float DACMaxHL=0;
SumDAL=0;SumDACMin=0;SumDACMax=0;SumDAG=0;SDEMax=Tank.Cap;SDEMin=0;
if(P4==1&&Tank.Cap>Zero&&day<364)
 {
  //PART 4: set limits on StoreDayEnd according to needs of next day.
  for(int n=0;n<48;n++)
  { //DA_LIWH: DADemand<DAIWH, allow for gas when CHP off change LIWH
   if(DAQ[n][5]>Zero)SumDAL+=DAQ[n][5]/2;
   if(DAQ[n][3]+Zero<CHPMin)SumDACMin+=(CHPMin-DAQ[n][4])/2;
   if(DAQ[n][3]<CHPMax&&(DAQ[n][3]+Zero)>CHPMin)
                    SumDACMax+=(CHPMax-DAQ[n][3])/2;//scope to charge
   if(DAQ[n][4]>Zero&&DAQ[n][3]>CHPMin-Zero)
                    SumDAG+=DAQ[n][4]/2;//scope to discharge

   if(SumDAG-(SumDAL+SumDACMin-HighDAHL)<0)
                    HighDAHL+=(HL_0*Tank.Cap+HL_c*(SDEMax+SumDAL+SumDACMin-HighDAHL-SumDAG))/2;
   if(SumDAG-(SumDAL+SumDACMin-LowDAHL)>SumDACMax)
                    LowDAHL+=(HL_0*Tank.Cap+HL_c*(SDEMin+SumDAL+SumDACMin-LowDAHL-SumDAG))/2;
   DACMaxHL+=HL_c*SumDACMax;
   //DACMax can be added (with increased heat losses) if that is how Min and Max converge

   //set store (current) day end limits...
   if(SumDAG<SumDAL+SumDACMin-HighDAHL)
                    {if(SDEMax>Tank.Cap-(SumDAL+SumDACMin-SumDAG-HighDAHL))
                      if(SDEMin<Tank.Cap-(SumDAL+SumDACMin-SumDAG-HighDAHL))
                      SDEMax=Tank.Cap-(SumDAL+SumDACMin-SumDAG-HighDAHL);
                    }
   //heat losses from DACMax only materialise, in addition to LowDAHL, if it is implemented
   if(SumDAG>SumDAL+SumDACMin+SumDACMax-LowDAHL-DACMaxHL)//mainly for days with SumDAG>HighCharge
                    {if(SDEMin<SumDAG-SumDAL-SumDACMin-SumDACMax-LowDAHL-DACMaxHL)
                      {if(SDEMax>SumDAG-SumDAL-SumDACMin-SumDACMax-LowDAHL-DACMaxHL)
                                 SDEMin=SumDAG-SumDAL-SumDACMin-SumDACMax-LowDAHL-DACMaxHL;
                      }
                    }
  }
  //PART 4A:charge store if not meeting final value
   for(int k=47;P4==1&&k+1>0&&(SDEMin-SDE)>Zero;k--)
```

```
                { HeadRoom=Tank.Cap;//resets for each k, necessary?
                  if(k==47)HeadRoom=Tank.Cap-SDE;
                  for(int q=k+1;q<48;q++)//figure the HeadRoom available later
                    if(Tank.Cap-StVary[q]<HeadRoom)HeadRoom=Tank.Cap-StVary[q];
                  if(Tank.Cap-SDE<HeadRoom)HeadRoom=Tank.Cap-SDE;

                  if(Av[k]==1&&0.5*(CHPMax-Q[k][3])<(SDEMin-SDE)&&0.5*(CHPMax-Q[k][3])<HeadRoom)
                    {Tank.CR[k]+=CHPMax-Q[k][3];Q[k][3]=CHPMax;}//if space, full pelt
                  else if (Av[k]==1&&0.5*(CHPMax-Q[k][3])>(SDEMin-SDE)&&(SDEMin-SDE)<HeadRoom)
                    {Tank.CR[k]+=2*(SDEMin-SDE);Q[k][3]+=2*(SDEMin-SDE);}

                  for(int q=k;q<48;q++)
                    { HL[q]=HL_0*Tank.Cap+HL_c*StVary[q];
                          if(q<47)StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                          if(Tank.Cap-StVary[q+1]<HeadRoom)HeadRoom=Tank.Cap-StVary[q+1];
                          if(q==47)SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                    }
                 }
  //PART 4B:discharge store if headroom not achieved.
   for(int r=47;P4==1&&SDE-SDEMax>Zero&&r+1>0;r--)//added CR
                {  //FootRoom=Tank.Cap;
                 if(r==47){FootRoom=SDE;if(StVary[r]<FootRoom)FootRoom=StVary[r];}
                  for(int q=r+1;q<48;q++)//WAS r+1 figure HR available later
                    if(StVary[q]<FootRoom)FootRoom=StVary[q];
                  if(SDE<FootRoom)FootRoom=SDE;

                 if(Q[r][3]>CHPMin+Zero)//reduce CHP to min or by amount required late in day
                 { if(SDE-SDEMax>0.5*(Q[r][3]-CHPMin)&&0.5*(Q[r][3]-CHPMin)<FootRoom)
                    {Tank.CR[r]-=Q[r][3]-CHPMin;Q[r][3]=CHPMin;}
                  else if(SDE-SDEMax>0.5*(Q[r][3]-CHPMin)&&0.5*(Q[r][3]-CHPMin)>FootRoom)
                    {Tank.CR[r]-=2.0*FootRoom;Q[r][3]-=2.0*FootRoom;}
                 }
                for(int q=r;q<48;q++)
                 { HL[q]=HL_0*Tank.Cap+HL_c*StVary[q];
                  if(q<47)StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                  if(q==47)SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                 }
   }
  }//the PART 4 overall if(storecap>zero) loop

//PART 5A: increase CHP earlier reduce CHP later
 for(int k=47;P5a==1&&Tank.Cap>0.5*CHPMin&&k>=0;k--)//>49/0 to (de)activate
  { L=48;CRTemp[k]=0.0;
   for(int K=47;K>=0;K--)//calculates CHPLater for rest of day, exceeding CHPMin
    { CHPLater[K]=0;
                if(K<47&&Q[K+1][3]>CHPMin+Zero)
                 CHPLater[K]=CHPLater[K+1]+0.5*(Q[K+1][3]-CHPMin);
                else if(K<47)CHPLater[K]=CHPLater[K+1];
                if(Q[K][3]+Zero<CHPMin&&CHPLater[K]>0.5*CHPMin&&L==48&&Av[K]==1)L=K;
    }//L is the final period where CHP can be increased ahead of excess CHP

   //working through the CHP increase periods before CHP as k reduces
   if((L<48&&k<=L&&Q[k][3]+Zero<CHPMin&&Av[k]==1)&&CHPLater[k]>0.5*CHPMin)//+1
```

```
{ VoidLoop=0;VoidLoop2=0;StVaryTemp[k]=StVary[k];
            SumCRT=0.0;J=48;CRTemp[k]=CHPMin-Q[k][4];//set a CRT[k] for period k, ready to tweak

            if(k<47)StVaryTemp[k+1]=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
            if(k==47)SDETemp=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
            SumCRT=0.5*CRTemp[k];

            for(int l=k+1;(SumCRT>Zero&&l<J)&&(StVaryTemp[k+1]<Tank.Cap&&SDETemp<Tank.Cap);l++)
              { CRTemp[l]=0.0;
                if((Q[l][3]>CHPMin+Zero)&&SumCRT-0.5*(Q[l][3]-CHPMin)>Zero)CRTemp[l]=-(Q[l][3]-CHPMin);
                else if(Q[l][3]>CHPMin+Zero){CRTemp[l]=-2.0*SumCRT;J=l;}//finish loop
               SumCRT+=0.5*CRTemp[l];

              if(l<47)StVaryTemp[l+1]=StVaryTemp[l]+0.5*(Tank.CR[l]-HL[l]+CRTemp[l]);
              if(l==47)SDETemp=StVaryTemp[47]+0.5*(Tank.CR[47]-HL[47]+CRTemp[47]);

              if(l<47&&((StVaryTemp[l+1]-Tank.Cap)>Zero||StVaryTemp[l+1]<-Zero))VoidLoop=1;
              if(l==47&&((SDETemp-SDEMax)>Zero||SDETemp<-Zero))VoidLoop2=1;

              if((SumCRT<Zero&&J==l)&&(VoidLoop==0&&VoidLoop2==0))//success on charge->discharge.
              { Tank.CR[k]+=CRTemp[k];//if charge then discharge success.
                Q[k][4]=0;
                Q[k][3]=Q[k][2]-(Q[k][1]-LostIWH[k])-Q[k][4]+Tank.CR[k];
                StVary[k+1]=StVaryTemp[k+1];
              for(int q=k+1;q<=J;q++)
                { Tank.CR[q]+=CRTemp[q];
                  Q[q][3]=Q[q][2]-(Q[q][1]-LostIWH[q])-Q[q][4]+Tank.CR[q];
                  CRTemp[q]=0.0;
                  if(q<47)StVary[q+1]=StVaryTemp[q+1];
                  if(q==47)SDE=SDETemp;
                }
              }
              }//end of loop with l++
    for(int q=k;q<48;q++)
            { if(q<47)StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
             if(q==47)SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
            }
    }
  }

//PART 5B: reduce CHP earlier to increase CHP later
 for(int k=0;P5b==1&&Tank.Cap>0.5*CHPMin&&k<48;k++)
  { L=0;CRTemp[k]=0;
   for(int K=0;K<48;K++)//calculates CHPEarlier for earlier in day, exceeding CHPMin
    { CHPEarlier[K]=0.0;
            StVaryTemp[K]=StVary[K];//new, removes any remnants of 5A StVary
            if(K==47)SDETemp=SDE;//new
            if(K>0&&Q[K-1][3]>CHPMin+Zero)
              CHPEarlier[K]=CHPEarlier[K-1]+0.5*(Q[K-1][3]-CHPMin);
            else if(K>0)CHPEarlier[K]=CHPEarlier[K-1];
            if(K>0&&Q[K][3]+Zero<CHPMin&&CHPEarlier[K]>0.5*(CHPMin-Q[K][4])&&Av[K]==1&&L==0)L=K;
            //L is the first period where CHP can be increased after excess CHP
    }
```

```
  if(L>0&&k>=L&&Q[k][3]+Zero<CHPMin&&Av[k]==1&&CHPEarlier[k]>0.5*(CHPMin-Q[k][4]))
    { VoidLoop=0;
        if(k<47)StVaryTemp[k+1]=StVary[k+1];else SDETemp=SDE;//added
        SumCRT=0.0;J=0;CRTemp[k]=CHPMin-Q[k][4];//J=0 change from 48
        //set a CRT[k] for period k, ready to tweak

        if(k>0&&k<47)StVaryTemp[k]=StVaryTemp[k+1]-0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
        else if(k==47)StVaryTemp[k]=SDETemp-0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
        SumCRT=0.5*CRTemp[k];//SumCRT=0.5*(CRTemp[k]-Q[k][4]);

        for(int l=k-1;(SumCRT>Zero&&l>=0)&&(StVaryTemp[k]>Zero)&&J==0;l--)//was[k-1]and J==48
          { CRTemp[l]=0.0;
            if(Q[l][3]>CHPMin+Zero&&SumCRT-0.5*(Q[l][3]-CHPMin)>Zero)CRTemp[l]=-(Q[l][3]-CHPMin);
            else if(Q[l][3]>CHPMin+Zero){CRTemp[l]=-2.0*SumCRT;J=l;}//finish loop

           SumCRT+=0.5*CRTemp[l];

           if(l<47)StVaryTemp[l]=StVaryTemp[l+1]-0.5*(Tank.CR[l]-HL[l]+CRTemp[l]);

           if(l>0&&l<47&&StVaryTemp[l]<-Zero)VoidLoop=1;

           if(SumCRT<Zero&&J==l&&VoidLoop==0)//success on discharge->charge. (SumCRT<Zero&&
             { Tank.CR[k]+=CRTemp[k];//if charge->discharge success.
                StVary[k]=StVaryTemp[k];
                Q[k][4]=0;//added
                Q[k][3]=Q[k][2]-(Q[k][1]-LostIWH[k])-Q[k][4]+Tank.CR[k];

                for(int q=k-1;q>=J;q--)//changed to q=k+1 from q=k
                  { Tank.CR[q]+=CRTemp[q];//more to less
                    Q[q][3]=Q[q][2]-(Q[q][1]-LostIWH[q])-Q[q][4]+Tank.CR[q];
                    CRTemp[q]=0.0;StVary[q+1]=StVaryTemp[q+1];//was q+1
                  }
             }
          }//end of loop with l--
        for(int q=k;q>=0;q--)//minus
        { if(q<47)StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
        if(q==47)SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
        }
    }
  }

//PARTS 6:Coordinated actions
//6. increase CHP earlier reduce gas later (acts at latest time)
L=48;J=48;
for(int k=47;P6==1&&Tank.Cap>Zero&&k>=0;k--)
  { CRTemp[k]=0.0;
    for(int K=47;K>k;K--)//calculates GasLater, was K>0
      { if(K==47)GasLater[K]=0.5*Q[K][4];
        else GasLater[K]=GasLater[K+1]+0.5*(HL_c*GasLater[K+1]+Q[K][4]);
        if((Q[K-1][3]+Zero<CHPMax)&&(GasLater[K]>Zero&&L==48))L=K-1;
        //L= final period where CHP can be increased ahead of gas use
        HLTemp[K]=0;
      }
```

```
  //working through the CHP increase periods before Gas as k reduces
  if(L<47&&k<=L&&Q[k][3]+Zero<CHPMax&&Av[k]==1&&GasLater[k+1]>Zero)//+1
   { VoidLoop=0;StVaryTemp[k]=StVary[k];SumCRT=0;J=48;
        //set a CRT[k] for period k, ready to tweak
        if(GasLater[k+1]>0.5*(CHPMax-Q[k][3]))
         CRTemp[k]=CHPMax-Q[k][3];
        else if(GasLater[k+1]<0.5*(CHPMax-Q[k][3]))
         CRTemp[k]=2*GasLater[k+1];
        SumCRT=0.5*CRTemp[k];
        for(int l=k;SumCRT>Zero&&l<J;l++)//J is the upper limit, intially 48
         { if(l>k)
            {CRTemp[l]=0.0;
                HLTemp[l]=HL_c*SumCRT;
                if(SumCRT-0.5*(HLTemp[l]+Q[l][4])>Zero)CRTemp[l]=-Q[l][4];
                else {CRTemp[l]=-2.0*SumCRT+HLTemp[l];J=l;}//finish loop
                SumCRT+=0.5*(CRTemp[l]-HLTemp[l]);
            }
          if(l<47)StVaryTemp[l+1]=StVaryTemp[l]+0.5*(Tank.CR[l]-HL[l]-HLTemp[l]+CRTemp[l]);
          if(l<47&&((StVaryTemp[l+1]-Tank.Cap)>Zero||StVaryTemp[l+1]<-Zero))VoidLoop=1;

          if(VoidLoop==1)
           { if(StVaryTemp[l+1]-Tank.Cap>Zero)
                 CRTemp[k]-=2.0*(StVaryTemp[l+1]-Tank.Cap)*pow(1-0.5*HL_c,l-k);
                if(StVaryTemp[l+1]<-Zero)
                 CRTemp[k]-=2.0*StVaryTemp[l+1]*pow(1-0.5*HL_c,l-k);
                //store levels outside the boundaries will be recalculated after l=k
                if(k<47)StVaryTemp[k+1]=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                if(k<47)HLTemp[k+1]=HL_0*Tank.Cap+HL_c*StVaryTemp[k+1];
                if(k==47)SDETemp=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                SumCRT=0.5*CRTemp[k];l=k;VoidLoop=0;
            }
   if(SumCRT<Zero&&J==l)//success on charge then discharge.
         { Tank.CR[k]+=CRTemp[k];//if charge then discharge success.
          Q[k][3]=Q[k][2]-(Q[k][1]-LostIWH[k])-Q[k][4]+Tank.CR[k];
          for(int q=k+1;q<J+1;q++)
            { Tank.CR[q]+=CRTemp[q];
                if(CRTemp[q]<-Zero)Q[q][4]+=CRTemp[q];
                Q[q][3]=Q[q][2]-(Q[q][1]-LostIWH[q])-Q[q][4]+Tank.CR[q];
                CRTemp[q]=0.0;StVary[q]=StVaryTemp[q];HL[q]+=HLTemp[q];
                if(q==48)SDE=SDETemp;
            }
         }
         }//end of loop with l++
   }
 }

//PART 7:remove residual LIWH by reducing CHP earlier noting store limits
J=48;
for(int k=47;P7==1&&Tank.Cap>Zero&&k>=1;k--)//was 0
 { L=48;
  LIWHLater[47]=0.5*LostIWH[47];
   for(int K=47;K>=0;K--)
        { CRTemp[K]=0;
```

```
                    if(K<47)LIWHLater[K]=LIWHLater[K+1]+0.5*(HL_c*LIWHLater[K+1]+LostIWH[K]);
                    if(Q[K][3]>CHPMin+Zero&&LIWHLater[K]>Zero&&L==48)L=K;
     }//L set as last period where CHP>Min before LIWH

    if(k<=L&&Q[k][3]>CHPMin+Zero&&L<48)
                   { StVaryTemp[k]=StVary[k];
                    if(LIWHLater[k]>0.5*(Q[k][3]-CHPMin))CRTemp[k]=-(Q[k][3]-CHPMin);
                    else CRTemp[k]=-2*LIWHLater[k];
                    SumCRT=0.5*CRTemp[k];
                    for(int l=k;SumCRT<-Zero&&l<48;l++)
                      { if(l>k)
                                  { HLTemp[l]=HL_c*SumCRT;
                                   if(SumCRT-0.5*HLTemp[l]+0.5*LostIWH[l]<Zero)
                                     {CRTemp[l]=LostIWH[l];SumCRT+=0.5*(CRTemp[l]-HLTemp[l]);}
                                   else {CRTemp[l]=-2.0*SumCRT;SumCRT=0;}//j=l removed end recharge
                                  }
                        if(l<47)StVaryTemp[l+1]=StVaryTemp[l]+0.5*(Tank.CR[l]+CRTemp[l]-HL[l]-HLTemp[l]);
                        if(l<47&&StVaryTemp[l+1]>Tank.Cap+Zero)
                                  {CRTemp[l]-=2.0*(StVaryTemp[l+1]-Tank.Cap);}
                        if(l<47&&StVaryTemp[l+1]<-Zero)//temp sto out limits
                                  {if(2.0*StVaryTemp[l+1]>CRTemp[k]*pow(1-0.5*HL_c,l-k))
                                     {CRTemp[k]-=2.0*StVaryTemp[l+1]*pow(1-0.5*HL_c,l-k);
                                      SumCRT=0.5*CRTemp[k];l=k;}
                                   else {CRTemp[k]=0;l=48;}
                                  }
                      }
                    Tank.CR[k]+=CRTemp[k];//change here

                    if(CRTemp[k]<-Zero)Q[k][3]=Q[k][2]-(Q[k][1]-LostIWH[k])-Q[k][4]+Tank.CR[k];//added minus
                    for(int q=k+1;q<48&&CRTemp[k]<-Zero;q++)
                      { HL[q]+=HLTemp[q];
                       if(CRTemp[q]>Zero){Tank.CR[q]+=CRTemp[q];LostIWH[q]-=CRTemp[q];}
                       //if(CRTemp[q]<-Zero)cout<<"blah!"<<endl;
                       //Tank.CR[q]+=CRTemp[q];LostIWH[q]-=CRTemp[q];
                       Q[q][3]=Q[q][2]-(Q[q][1]-LostIWH[q])-Q[q][4]+Tank.CR[q];//k->q
                    }
                    for(int i=k;i<48&&CRTemp[k]<-Zero;i++)
                      {CRTemp[i]=0.0;StVary[i]=StVaryTemp[i];
                      }//if(StVary[i]>Tank.Cap+Zero)cout<<"day, k,i, StVary: "<<day<<","<<k<<","<<i<<","<<StVary[i]<<endl;}//was k+1
                   }//end of conditional
  }

for(int n=0;n<48;n++)
  {HL[n]=HL_0*Tank.Cap+HL_c*StVary[n];
   //if(StVary[n+1]-(StVary[n]+0.5*(Tank.CR[n]-HL[n]))>0.01&&n<47)
   //cout<<day<<" "<<StVary[n+1]-(StVary[n]+0.5*(Tank.CR[n]-HL[n]))<<endl;
   if(n<47)StVary[n+1]=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
   //if(StVary[n+1]>Tank.Cap)cout<<"1-7 day,n+1, StVary: "<<day<<","<<n+1<<","<<StVary[n+1]<<endl;
   if(n==47)SDE=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
  }

//PART 8: Looking to rearrange production timing so that timing is optimised
bool LoSCHi,Hi0Lo;//low-storecap-high, high-0-low
```

```
float dCHP=0.05;//now moving 0.025 MWh at a time
for(int w=0;Tank.Cap>Zero&&P8==1&&w<96;w++)//runs this many times to repeat optimisaton
  {
for(int l=0;l<48;l++)
  { Hi.Price=Price[l]+Zero;Hi.t=l;Lo.Price=Price[l]-Zero;Lo.t=l;
    //Find High/Low PPs accessible later. PP=price period
    LoSCHi=0;Hi0Lo=0;
    for(int k=l+1;Av[l]==1&&(LoSCHi==0||Hi0Lo==0)&&k<48;k++) //loop stops if store->limits or k=48
      { //determine if store->limits in that step if not (dis)charged
                    if(StVary[k]+0.5*dCHP*pow(1-0.5*HL_c,k-l-1)>Tank.Cap)LoSCHi=1;//0->t=k can be high PP
                    if(StVary[k]-0.5*dCHP*pow(1-0.5*HL_c,k-l-1)<0)Hi0Lo=1;//0->t=k can be low PP
      //seek high price later
                    if(LoSCHi==0&&Price[k]*pow(1-0.5*HL_c,k-l)>Hi.Price)
                      if(Q[k][3]>CHPMin+dCHP*pow(1-0.5*HL_c,k-l)&&Q[l][3]+dCHP<CHPMax)
                        {Hi.Price=Price[k]*pow(1-0.5*HL_c,k-l);Hi.t=k;}
      //seek low price later
      if(Hi0Lo==0&&Price[k]*pow(1-0.5*HL_c,l-k)<Lo.Price&&Av[k]==1)
                    if(Q[l][3]>CHPMin+dCHP&&Q[k][3]+dCHP*pow(1-0.5*HL_c,k-l)<CHPMax)
                      {Lo.Price=Price[k]*pow(1-0.5*HL_c,l-k);Lo.t=k;}
      }
    //Find Higher/Lower PPs accessible earlier
    LoSCHi=0;Hi0Lo=0;
    for(int k=l-1;Av[l]==1&&(LoSCHi==0||Hi0Lo==0)&&k+1>0;k--)
      { if(StVary[k+1]+0.5*dCHP>Tank.Cap)LoSCHi=1;
                    if(StVary[k+1]-0.5*dCHP<0)Hi0Lo=1;
                    if(Hi0Lo==0&&Price[k]*pow(1-0.5*HL_c,k-l)>Hi.Price&&Av[k]==1)
                      if(Q[l][3]<CHPMax-dCHP*pow(1-0.5*HL_c,l-k)&&Q[k][3]>CHPMin+dCHP)
                        {Hi.Price=Price[k]*pow(1-0.5*HL_c,k-l);Hi.t=k;}
                    if(LoSCHi==0&&Price[k]*pow(1-0.5*HL_c,l-k)<Lo.Price&&Av[k]==1)
                      if(Q[l][3]>CHPMin+dCHP*pow(1-0.5*HL_c,l-k)&&Q[k][3]+dCHP<CHPMax)
                        {Lo.Price=Price[k]*pow(1-0.5*HL_c,l-k);Lo.t=k;}
      }

    //Lo(Hi).t emerges as the lowest(highest) PP accessible by store movement
    //if more is gained by moving elec prod to high PP then do so, or vice versa
    //could repeat this if there is yet more to take off/add on currently
    if(Hi.Price-Price[l]>Price[l]-Lo.Price&&Hi.t!=Lo.t)
      { if(Hi.t<l)
                      {Tank.CR[Hi.t]-=dCHP;Tank.CR[l]+=dCHP*pow(1-0.5*HL_c,l-Hi.t);
                        Q[Hi.t][3]-=dCHP;Q[l][3]+=dCHP*pow(1-0.5*HL_c,l-Hi.t);
                        for(int L=Hi.t+1;L<l+1;L++)
                          {StVary[L]=StVary[L-1]+0.5*(Tank.CR[L-1]-HL[L-1]);
                                      HL[L]=HL_0*Tank.Cap+HL_c*StVary[L];
                          }
                      }
                    if(Hi.t>l)
                      {Tank.CR[l]+=dCHP;Tank.CR[Hi.t]-=dCHP*pow(1-0.5*HL_c,Hi.t-l);
                        Q[Hi.t][3]-=dCHP*pow(1-0.5*HL_c,Hi.t-l);Q[l][3]+=dCHP;
                        for(int L=l+1;L<Hi.t+1;L++)
                          {StVary[L]=StVary[L-1]+0.5*(Tank.CR[L-1]-HL[L-1]);
                                      HL[L]=HL_0*Tank.Cap+HL_c*StVary[L];
                          }
                      }
```

```
    }
   if(Hi.Price-Price[l]<Price[l]-Lo.Price&&Hi.t!=Lo.t)
    { if(Lo.t<l)
              {Tank.CR[Lo.t]+=dCHP;Tank.CR[l]-=dCHP*pow(1-0.5*HL_c,l-Lo.t);
               Q[Lo.t][3]+=dCHP;Q[l][3]-=dCHP*pow(1-0.5*HL_c,l-Lo.t);
               for(int L=Lo.t+1;L<l+1;L++)
                {StVary[L]=StVary[L-1]+0.5*(Tank.CR[L-1]-HL[L-1]);
                      HL[L]=HL_0*Tank.Cap+HL_c*StVary[L];
                }
              }
             if(Lo.t>l)
              {Tank.CR[l]-=dCHP;Tank.CR[Lo.t]+=dCHP*pow(1-0.5*HL_c,Lo.t-l);
               Q[Lo.t][3]+=dCHP*pow(1-0.5*HL_c,Lo.t-l);Q[l][3]-=dCHP;
               for(int L=l+1;L<Lo.t+1;L++)
                {StVary[L]=StVary[L-1]+0.5*(Tank.CR[L-1]-HL[L-1]);
                      HL[L]=HL_0*Tank.Cap+HL_c*StVary[L];
                }
              }
    }
 for(int n=0;n<48;n++)
  {HL[n]=HL_0*Tank.Cap+HL_c*StVary[n];
   if(n<47)StVary[n+1]=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
   //if(Tank.CR[n]<((0-StVary[n])/0.5)+HL[n])cout<<"M";
   if(n==47)SDE=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
  }
  }
  }//repeats part 8

 int SwitchCount=0;
 IWHCaught=0;IntLostIWH=0;CHPHeatSales=0;GasHeatSales=0;IntDem=0;CHPElecSales=0;
 //PART 9: add the production up each day and add to the annual total
 for(int k=0;k<48;k++)
  { IWHCaught+=Q[k][1]/2;CHPHeatSales+=Q[k][3]/2;AnnLoss+=HL[k]/2;GasHeatSales+=Q[k][4]/2;
   IntLostIWH+=LostIWH[k]/2;IntDem+=Q[k][2]/2;
   if(Av[k]==1)
    {CHPElecSales+=(CHPElecCap-(Q[k][3]/CHPZ))/2;
             ElecRevenue+=Price[k]*(CHPElecCap-(Q[k][3]/CHPZ))/2;
    }
   if(k==0&&((CHPDayEnd<Zero&&Q[k][3]>Zero)||(CHPDayEnd>Zero&&Q[k][3]<Zero)))SwitchCount++;
   if(k>0&&((Q[k-1][3]<Zero&&Q[k][3]>Zero)||(Q[k-1][3]>Zero&&Q[k][3]<Zero)))SwitchCount++;
   if(k==47)CHPDayEnd=Q[k][3];

   //if(StVary[k]>Tank.Cap+Zero){cout<<"E";if(day==364&&k==47)cout<<endl;}
   float t;t=static_cast<float>((day-1)*24+k/2.0);
   //PRINT RESULTS:
   if(Av[k]==1)
    { fout<<(day-1)*48+k<<"\t"<<t<<"\t"<<Q[k][2]<<"\t"<<Q[k][3]<<"\t"<<CHPElecCap-Q[k][3]/CHPZ<<"\t";
             fout<<Q[k][1]<<"\t"<<LostIWH[k]<<"\t"<<Q[k][4]<<"\t"<<StVary[k]<<"\t"<<Tank.CR[k]<<"\t"<<HL[k];
             fout<<"\t"<<Price[k]<<"\t"<<Price[k]*(CHPElecCap-Q[k][3]/CHPZ)/2<<endl;
    }
   else
    { fout<<(day-1)*48+k<<"\t"<<t<<"\t"<<Q[k][2]<<"\t"<<Q[k][3]<<"\t"<<0<<"\t";
             fout<<Q[k][1]<<"\t"<<LostIWH[k]<<"\t"<<Q[k][4]<<"\t"<<StVary[k]<<"\t"<<Tank.CR[k]<<"\t"<<HL[k];
```

```
                        fout<<"\t"<<Price[k]<<"\t"<<0<<endl;
      }
   }

 AnnIWHCaught+=IWHCaught;AnnCHPSales+=CHPHeatSales;AnnGasSales+=GasHeatSales;
 AnnCHPElecSales+=CHPElecSales;
 AnnIWHLost+=IntLostIWH;AnnDem+=IntDem;AnnSwitchCount+=SwitchCount;

 if(Tank.Cap>Zero)StoreDayStart=SDE; //for continuity of stored volume to the next day.
 if(Tank.Cap>Zero&&day==364)StoreYearEnd=SDE;

 }//day looping

  PrimaryEnergyInput=250000*13.25*1000.0/3600.0; //for QI Calculation
  TotalAnnualHeat=AnnCHPSales+AnnGasSales+AnnIWHCaught-AnnIWHLost;//-AnnLoss;
  QI=(318*AnnCHPElecSales/PrimaryEnergyInput)+(120*AnnCHPSales/PrimaryEnergyInput);
  if(QI>100.0)ROCRev=ROCValue*1.9*AnnCHPElecSales;
  else ROCRev=ROCValue*(1.5+(1.9-1.5)*QI/100.0)*AnnCHPElecSales;
  //last two terms were already in the heat generation: +StoreYearEnd-StoreYearStart;

  if(AnnGasSales<Zero){AnnGasSales=0;}

  float M=1000000;//one million, to reduce some numbers below
  //List results for operator
  if(A==0&&B==0)cout<<"Cap\tADem\tAHeat\tACHPHS\tACHPES\tAGS\tER-9M\t";
  if(A==0&&B==0)cout<<"QI\tRR-20M\tAIWHD\tALoss\tSwitches"<<endl;
  cout<<Tank.Cap<<"\t"<<AnnDem<<"\t"<<TotalAnnualHeat<<"\t"<<AnnCHPSales<<"\t";
  cout<<AnnCHPElecSales<<"\t"<<AnnGasSales<<"\t"<<ElecRevenue-9*M<<"\t"<<QI<<"\t";
  cout<<ROCRev-20*M<<"\t"<<AnnIWHCaught-AnnIWHLost<<"\t"<<AnnLoss<<"\t"<<AnnSwitchCount<<endl;
  fout.close();fin7.close();fin.close();fin2.close();
 }//A-Loop changes the store capacity

}//B-Loop changes demand values

  return 0;
}
```

10.5.4 Base Code for Interconnected heat networks

```
//CityBase11.cc Prints base heat source pattern (no store) use: ./CityBase11 150
#include <iostream>
#include <cmath>
#include <fstream>
using namespace std;
class HeatSource{
public:
  float DH1[7][48];//could be priority,DH2[7][48],DH3[7][48]; //time+rate of DH prod, day1= Sat
  float Op[52]; //operational weeks
  float Prod,Max,Min,Heat,Elec;
  int Av;
};
void SumElements748(float matrixName[7][48],float &Sum);
void SumElements52(float ArrayName[52],float &Sum2);
float ShefERF(float heat,int Avail)
{ float elec;
```

```
  if(Avail==1&&heat<18.0)elec=20.0-(4.8/18.0)*heat;
  else if(Avail==1&&heat>18.0&&heat<33.0)elec=15.2-(2.0/15.0)*(heat-18.0);
  else if(Avail==1&&heat>33.0)elec=13.2;
  else elec=0;return elec;
}
float ShefBM(float heat,int Avail)
{ float elec;
  if(Avail==1&&heat<25.0)elec=31.0-heat/6.0;
  else if(Avail==1&&heat>25.0)elec=31.0-25.0/6.0;
  else elec=0;return elec;
}

int main(int argc,char* argv[]) //Command line inputs,scenario only
{
  HeatSource CHP1,CHP2;
  float Demand,HNDem,GasHeatSold,GasHeat,CHPHeatSold,dCHP,LHS1,LHS2;
  float AnnualHNDemand,Zero,ROCValue,GBEff,SpotPrice,GasPrice;
  AnnualHNDemand=0;Zero=0.00001;ROCValue=45.0;GBEff=0.8;GasPrice=25.0;dCHP=0.05;
  ifstream fin,fin2,fin3,fin4;
  ofstream fout;
  float CurrentCost,NewCost1,NewCost2;
  CHP1.Max=33.0001;CHP2.Max=25.0001;GasHeatSold=0;GasHeat=0;CHPHeatSold=0;
  if(argc>1){sscanf(argv[1],"%f",&Demand);}else{cout<<"Demand (GWh/a)? ";cin>>Demand;}
  fout.open("Ser.dat");
  fin.open("Demand120.dat");fin2.open("AvailBR.dat");fin3.open("AvailBM.dat");fin4.open("SpotData.dat");
  for(int time=0;time<17472;time++)//time in half-hours 0:17472, 52 weeks.
    { int n,l,m;//Half hour No, Week No, Day of week 0=Sat
      n=time%48;l=(time/336);m=(time/48)-l*7;CHP1.Heat=0;CHP2.Heat=0;//Heat outputs
      fin>>HNDem;fin2>>CHP1.Av;fin3>>CHP2.Av;fin4>>SpotPrice;//demand,avail,spot price
      HNDem=HNDem*Demand/120;
      CHP1.Elec=ShefERF(CHP1.Heat,CHP1.Av);CHP2.Elec=ShefBM(CHP2.Heat,CHP2.Av);
      GasHeat=HNDem;
      bool Loop1=1;
      int a=0;

      //Economic heat calculation
      while(Loop1==1&&((CHP1.Av==1&&CHP1.Heat+dCHP<CHP1.Max)||(CHP2.Av==1&&CHP2.Heat+dCHP<CHP2.Max)))
                    { CurrentCost=GasPrice*GasHeat/GBEff;
                      CurrentCost-=SpotPrice*(CHP1.Elec+CHP2.Elec);
                      CurrentCost-=ROCValue*(CHP1.Elec+1.9*CHP2.Elec);
                      NewCost1=CurrentCost+Zero;NewCost2=CurrentCost+Zero;
                      //CHP1 change option
                      if(GasHeat-dCHP>Zero)
                        { if(CHP1.Av==1&&CHP1.Heat+dCHP<CHP1.Max)
                                      { float NewCHP1H=CHP1.Heat+dCHP;
                                        NewCost1=GasPrice*(GasHeat-dCHP)/GBEff;
                                        NewCost1-=(SpotPrice*(ShefERF(NewCHP1H,CHP1.Av)+CHP2.Elec);
                                        NewCost1-=ROCValue*(ShefERF(NewCHP1H,CHP1.Av)+1.9*CHP2.Elec);
                                      }
                          if(CHP2.Av==1&&CHP2.Heat+dCHP<CHP2.Max)
                                      { float NewCHP2H=CHP2.Heat+dCHP;
                                        NewCost2=GasPrice*(GasHeat-dCHP)/GBEff;
                                        NewCost2-=SpotPrice*(CHP1.Elec+ShefBM(NewCHP2H,CHP2.Av));
                                        NewCost2-=ROCValue*(CHP1.Elec+1.9*ShefBM(NewCHP2H,CHP2.Av));
                                      }
                        }
                      if(NewCost1<CurrentCost&&NewCost1<NewCost2-Zero)
                        {CHP1.Heat=CHP1.Heat+dCHP;CHP1.Elec=ShefERF(CHP1.Heat,CHP1.Av);
                          GasHeat=HNDem-(CHP1.Heat+CHP2.Heat);}
                      else if(NewCost2<CurrentCost&&NewCost2<NewCost1-Zero)
                        {CHP2.Heat=CHP2.Heat+dCHP;CHP2.Elec=ShefBM(CHP2.Heat,CHP2.Av);
```

```
                    GasHeat=HNDem-(CHP1.Heat+CHP2.Heat);}
                  else Loop1=0;
                  a++;
                 }
LHS1=0;LHS2=0; AnnualHNDemand+=HNDem/2;
fout<<time<<"\t"<<0.5*time<<"\t"<<HNDem<<"\t"<<CHP1.Heat<<"\t"<<CHP1.Elec<<"\t"<<CHP2.Heat<<"\t";
fout<<CHP2.Elec<<"\t"<<GasHeat<<"\t"<<SpotPrice<<"\t"<<LHS1<<"\t"<<LHS2<<endl;
   }//time looping
  cout<<"HN Demand: "<<AnnualHNDemand<<endl;
  fout.close();fin.close();fin2.close();fin3.close();fin4.close();

  return 0;
}
void SumElements748(float matrixName[7][48],float &Sum)
{ Sum=0.0;
  for(int m=0;m<7;m++){for(int n=0;n<48;n++)Sum+=matrixName[m][n];}
}
void SumElements52(float ArrayName[52],float &Sum2)
{ Sum2=0.0;
  for(int n=0;n<52;n++)Sum2+=ArrayName[n];
}
```

10.5.5 Code for interconnected networks with heat storage

```
//CityStore91.cc
//use:./CityStore91 0 30 3 50 1 >tmpfile uses 3 Caps 0-30, 50% boiler in CHP1 site, 1 to activate part 9
#include <iostream>
#include <cmath>
#include <fstream>
using std::cin;using std::cout;using std::endl;using std::ifstream;using std::ofstream;
class HeatStore{
public:
  float Stored,Cap;//cap = capacity
  float CR[48],CRNHPC[48];//charge rate
};
class HighOrLow{
public:
  int t,CHP;
  float Price;
};
class CHP{
public:
  float Max,Min,AnnHSold,AnnPSold;//max+min thermal outputs, heat+power sold (MWh/a)
  float QI,QI_t,QI_e,PEI,R100,R0;//QI, primary energy + ROC coefficients
  int Av[48],DAAv[48];
  float NHPC[48],NHPCDown[48],RH[48],RHLater[48];//heat prod cost(more/less) and rejected heat
};
class Boiler{
public:
  float Eff,GPrice,FuelUse,AnnHSold;
  float NHPC[48],HLater[48];
};
float ERF(float heat,int Avail);//ERF CHP
float BM(float heat,int Avail);//BM CHP
float ElecRevenue(float Price,float PSold);
float ROCRevenue(float RValue,float QI,float ROC100,float ROC0,float PSold);
void NHPCCalc(float &NHPC,int Av,float now,float max,float R_100,float RVal,float Price,float Elec1,float Elec2,float dCHP);

int main(int argc,char* argv[])
{ HeatStore Tank;CHP CHP1,CHP2;Boiler GB;
  CHP1.Max=33;CHP1.Min=0;CHP1.QI_e=370;CHP1.QI_t=120;CHP1.R100=1;CHP1.R0=0;
  CHP2.Max=25;CHP2.Min=0;CHP2.QI_e=318;CHP2.QI_t=120;CHP2.R100=1.9;CHP2.R0=1.5;
```

```
 GB.Eff=0.8;GB.GPrice=25;
 float AnnDem,AnnLoss,StMin,StMax,GasF1,dCHP,Zero;
 int AnnSwitchCount,AnnSwitch2Count,L,J,StNo,DemNo;
 HighOrLow Hi,Lo,NowHi,NowLo;
 bool P8;
 dCHP=0.05,Zero=0.00001;//CHP and negligible increment
 if(argc>1){sscanf(argv[1],"%f",&StMin);}else{cout<<"Min Store Value ";cin>>StMin;}
 if(argc>2){sscanf(argv[2],"%f",&StMax);}else{cout<<"Max Store Value ";cin>>StMax;}
 if(argc>3){sscanf(argv[3],"%d",&StNo);}else{cout<<"Number of Store Values ";cin>>StNo;}
 if(argc>4){sscanf(argv[4],"%f",&GasF1);}
 else{cout<<"% of gas boiler use assigned with CHP1 ";cin>>GasF1;}
 if(GasF1>100||GasF1<-Zero)return -1;
 if(argc>5){sscanf(argv[5],"%d",&P8);}else{cout<<" Part 8 Active? (1-Y/0-N) ";cin>>P8;}
 //if(argc>5){sscanf(argv[5],"%d",&DemNo);}else{cout<<"Number of Demand Values ";cin>>DemNo;}

 float StYearStart,StYearEnd,StDayStart,SDE,SDETemp,CRMin,SDEMin,SDEMax,CHPDayEnd,CHP2DayEnd;//SDE=StDayEnd
 float StValYrStart,StValYrEnd,StValDayStart,SVDE;
 float GasHeatSales,CHPHeatSales,CHPElecSales,ElecRev,ROCRev,CHP2HeatSales,CHP2ElecSales,ElecRev2,ROCRev2;
 float Q[48][11],DAQ[48][11];
 float StVary[48],StVaryTemp[48],StVal[48],CRTemp[48],Price[48],HPrice[48],CHPEarlier[48];//add val,price
 float CHPLater[48],CHP2Earlier[48],CHP2Later[48],HL[48],HLTemp[48];
 float HL_0,HL_c;//Heat Loss Power, HL[k]=HL_0*HWTank.StorCap+HL_c*StoredVary[k]
 float IntLHS1,IntLHS2,IntDem,SumCRT,HeadRoom,FootRoom,TotalAnnualHeat,SumDAL,SumDAL2,SumDACMin,SumDACMax,SumDAC2Max,SumDAG;
 float RVal=45.0;//£/ROC, 1.9 ROCs for biomass CHP commissioned 2015/16
 bool VoidLoop,VoidLoop2,P3A,P3B,P3C,P4,P5a,P5b,P6,P7;
 ifstream fin,fin2,fin3,fin7;
 ofstream fout;
 P3A=1;P3B=1;P3C=1;P4=1;P5a=1;P5b=1;P6=1;P7=1;//P8=1  //active parts

 for(int A=0;A<StNo;A++)//repeats for different store capacities
 {
 fin.open("Ser.dat");fin2.open("AvailBR.dat");fin3.open("AvailBM.dat");
 fin7.open("SpotData.dat");fout.open("NewSer.dat");
 StYearStart=0;StValYrStart=0;StYearEnd=0;StDayStart=StYearStart;SVDE=0;SDE=0;SDETemp=0;
 if(StNo>1)Tank.Cap=static_cast<float>(StMin+A*(StMax-StMin)/(StNo-1));else Tank.Cap=StMin;
 HL_0=0.001;HL_c=0.0005;//HEAT LOSS: HL_0*Cap+HL_c*Stored kW,  no store-no loss
 //Initialise Annual Parameters
 AnnDem=0;CHP1.AnnHSold=0;CHP1.QI=101;CHP2.QI=101;CHP2.AnnHSold=0;GB.AnnHSold=0;CHP1.AnnPSold=0;CHP2.AnnPSold=0;
 Tank.Stored=StDayStart;ElecRev=0;ElecRev2=0.0;AnnSwitchCount=0;AnnSwitch2Count=0;AnnLoss=0;
 CHPDayEnd=CHP1.Min;//CHPDayEnd reset at end of each day to determine any switches on/off
 //set day ahead (DA) values ready for first day to use:
 for(int n=0;n<48;n++){fin2>>CHP1.DAAv[n];fin3>>CHP2.DAAv[n];for(int j=0;j<11;j++)fin>>DAQ[n][j];}

for(int day=1;day<365;day++)//StDayStart value set @ end of previous day
{ GasHeatSales=0;CHPHeatSales=0;CHPElecSales=0;
 IntLHS1=0;IntLHS2=0;IntDem=0;CHP2HeatSales=0;CHP2ElecSales=0;
 //set values of arrays for day and heat losses
 for(int n=0;n<48;n++)
   { Tank.CR[n]=0;Tank.CRNHPC[n]=0;CRTemp[n]=0;GB.HLater[n]=0;CHP1.RHLater[n]=0;CHP2.RHLater[n]=0;
     StVary[n]=StDayStart;StVaryTemp[n]=StVary[n];StVal[n]=StValDayStart;
     HL[n]=0;HLTemp[n]=0;//heat losses for tank will be set later
     for(int j=0;j<11;j++)Q[n][j]=DAQ[n][j];//new order
     CHP1.Av[n]=CHP1.DAAv[n];CHP2.Av[n]=CHP2.DAAv[n];//load availability
     CHP1.RH[n]=Q[n][9];CHP2.RH[n]=Q[n][10];
     if(day<364){for(int j=0;j<11;j++)fin>>DAQ[n][j];fin2>>CHP1.DAAv[n];fin3>>CHP2.DAAv[n];}//DA from file
     fin7>>Price[n];//for economic optimisation
   }

 //0. Calculate Net Heat Production Costs (NHPCs) with function NHPCCalc
 for(int i=0;i<48;i++)
   { GB.NHPC[i]=GB.GPrice/GB.Eff;//£/MWh(t)
```

```
NHPCCalc(CHP1.NHPC[i],CHP1.Av[i],Q[i][3],CHP1.Max,CHP1.R100,RVal,Price[i],ERF(Q[i][3],CHP1.Av[i]),ERF(Q[i][3]+dCHP,CHP1.Av[i]),dCHP);
NHPCCalc(CHP2.NHPC[i],CHP2.Av[i],Q[i][5],CHP2.Max,CHP2.R100,RVal,Price[i],BM(Q[i][5],CHP2.Av[i]),BM(Q[i][5]+dCHP,CHP2.Av[i]),dCHP);
//if(day==185)cout<<CHP1.Av[i]<<"\t"<<CHP2.Av[i]<<endl;
   }

  //PART 1,2,3: uncoordinated action at one time of day, each affect StDayEnd
  for(int k=0;Tank.Cap>Zero&&k<48;k++)//store present
   { //1. Set heat and value losses
    HL[k]=HL_0*Tank.Cap+HL_c*StVary[k];
    if(k<47)
      {StVary[k+1]=StVary[k]+0.5*(Tank.CR[k]-HL[k]);StVaryTemp[k+1]=StVary[k+1];
                    StVal[k+1]=StVal[k]+0.5*(Tank.CR[k]*Tank.CRNHPC[k]-HL[k]*StVal[k]/StVary[k]);}
    else {SDE=StVary[47]+0.5*(Tank.CR[47]-HL[47]);SDETemp=SDE;
      SVDE=StVal[47]+0.5*(Tank.CR[k]*Tank.CRNHPC[k]-HL[k]*StVal[k]/StVary[k]);}

    //2. Make up for heat losses if tank fully empty
    CRMin=HL[k]-2*StVary[k];
    //2a. use any reject heat 1/2
    if(Tank.CR[k]<CRMin-Zero&&CHP1.RH[k]>Zero)
      {if(CHP1.RH[k]<CRMin-Tank.CR[k]){Tank.CR[k]+=CHP1.RH[k];Tank.CRNHPC[k]=0;CHP1.RH[k]=0;}
                    else {CHP1.RH[k]-=CRMin-Tank.CR[k];Tank.CR[k]=CRMin;Tank.CRNHPC[k]=0;}
      }
    if(Tank.CR[k]<CRMin-Zero&&CHP2.RH[k]>Zero)
      {if(CHP2.RH[k]<CRMin-Tank.CR[k]){Tank.CR[k]+=CHP2.RH[k];Tank.CRNHPC[k]=0;CHP2.RH[k]=0;}
                    else {CHP2.RH[k]-=CRMin-Tank.CR[k];Tank.CR[k]=CRMin;Tank.CRNHPC[k]=0;}
      }
      //2b. use lowest NHPC
    while(CHP1.NHPC[k]<CHP2.NHPC[k]&&CHP1.NHPC[k]<GB.NHPC[k]&&Tank.CR[k]<CRMin)
      {Q[k][3]+=dCHP;Tank.CR[k]+=dCHP;Tank.CRNHPC[k]=CHP1.NHPC[k];
NHPCCalc(CHP1.NHPC[k],CHP1.Av[k],Q[k][3],CHP1.Max,CHP1.R100,RVal,Price[k],ERF(Q[k][3],CHP1.Av[k]),ERF(Q[k][3]+dCHP,CHP1.Av[k]),dCHP);
      }
    while(CHP2.NHPC[k]<CHP1.NHPC[k]&&CHP2.NHPC[k]<GB.NHPC[k]&&Tank.CR[k]<CRMin)
      {Q[k][5]+=dCHP;Tank.CR[k]+=dCHP;Tank.CRNHPC[k]=CHP2.NHPC[k];
NHPCCalc(CHP2.NHPC[k],CHP2.Av[k],Q[k][5],CHP2.Max,CHP2.R100,RVal,Price[k],BM(Q[k][5],CHP2.Av[k]),BM(Q[k][5]+dCHP,CHP2.Av[k]),dCHP);
      }
    //2c. Top up with gas as last resort
    if(Tank.CR[k]<CRMin-Zero)
      {Q[k][7]+=(CRMin-Tank.CR[k]);Tank.CR[k]=CRMin;Tank.CRNHPC[k]=GB.NHPC[k];}

    //3A. Raise CHP to its minimum level: d(Q_CHP+Q_G)-dCR=0 occurs e.g. if(Dem<CHPMin)
    //STARTED WITH NECESSARY CHANGES
    // if(P3A==0&&CHP1.Av[k]==1&&Q[k][3]+Zero<CHP1.Min&&StVary[k]+0.5*(Tank.CR[k]-HL[k]+CHP1.Min-Q[k][7])<Tank.Cap)
    //{ Q[k][3]=CHP1.Min;Tank.CRNHPC[k]=(Tank.CRNHPC[k]*Tank.CR[k]+CHP1.NHPC[k]*(CHP1.Min-Q[k][7]);Tank.CR[k]+=CHP1.Min;
    //                  if(Q[k][7]>Zero){Tank.CR[k]-=Q[k][7];Q[k][7]=0;}
    //}
    //if(P3A==0&&CHP2.Av[k]==1&&Q[k][5]+Zero<CHP2.Min&&StVary[k]+0.5*(Tank.CR[k]-HL[k]+CHP2.Min-Q[k][7])<Tank.Cap)
    //{ Q[k][5]=CHP2.Min;Tank.CR[k]+=CHP2.Min;Tank.CRNHPC[k]=CHP2.NHPC[k];
    //                  if(Q[k][7]>Zero){Tank.CR[k]-=Q[k][7];Q[k][7]=0;}
    //}
    //3B. Add LHS1/2 to store if there is room
    if(P3B==1)
      {if(CHP1.RH[k]>Zero&&(StVary[k]+0.5*(Tank.CR[k]-HL[k]+CHP1.RH[k])<Tank.Cap))
                      {Tank.CR[k]+=CHP1.RH[k];CHP1.RH[k]=0.0;Tank.CRNHPC[k]=0;}
                    else if(CHP1.RH[k]>Zero&&StVary[k]+0.5*(Tank.CR[k]-HL[k])+Zero<Tank.Cap)
                      {Tank.CR[k]+=2.0*(Tank.Cap-(StVary[k]+0.5*(Tank.CR[k]-HL[k])));Tank.CRNHPC[k]=0;
                        CHP1.RH[k]=Q[k][5]+Q[k][3]+Q[k][7]-Tank.CR[k]-Q[k][2];//[1]
                      }
                    if(CHP2.RH[k]>Zero&&(StVary[k]+0.5*(Tank.CR[k]-HL[k]+CHP2.RH[k])<Tank.Cap))
                      {Tank.CR[k]+=CHP2.RH[k];CHP2.RH[k]=0.0;Tank.CRNHPC[k]=0;}
                    else if(CHP2.RH[k]>Zero&&StVary[k]+0.5*(Tank.CR[k]-HL[k])+Zero<Tank.Cap)
                      {Tank.CR[k]+=2.0*(Tank.Cap-(StVary[k]+0.5*(Tank.CR[k]-HL[k])));Tank.CRNHPC[k]=0;
```

```
                        CHP2.RH[k]=Q[k][5]+Q[k][3]+Q[k][7]-Tank.CR[k]-Q[k][2];//[1]
                       }
     }
    //3C. Discharge store to remove higher NHPCs (not just gas)
if(P3C==1)
 {
   if(Q[k][7]>Zero&&(StVary[k]+0.5*(Tank.CR[k]-HL[k]-Q[k][7])>Zero))//out &&GB.NHPC[k]>StVal[k]/StVary[k]
     {Tank.CR[k]-=Q[k][7];Q[k][7]=0.0;}//Tank.CRNHPC[k]=StVal[k]/StVary[k];
   else if(Q[k][7]>Zero&&GB.NHPC[k]>StVal[k]/StVary[k]&&StVary[k]+0.5*(Tank.CR[k]-HL[k])>Zero)
     if(StVary[k]+0.5*(Tank.CR[k]-HL[k]-Q[k][7])<-Zero)
                    {Tank.CR[k]-=2.0*StVary[k]+Tank.CR[k]-HL[k];
                     Q[k][7]=Q[k][2]+Tank.CR[k]+CHP1.RH[k]+CHP2.RH[k]-Q[k][3]-Q[k][5];
                    }
   if((CHP1.NHPC[k]>CHP2.NHPC[k]||CHP2.Av[k]!=1)&&Q[k][3]>Zero&&CHP1.NHPC[k]>StVal[k]/StVary[k]&&(StVary[k]+0.5*(Tank.CR[k]-HL[k]-
Q[k][3])>Zero))
     {Tank.CR[k]-=Q[k][3];Q[k][3]=0.0;}
   else if((CHP1.NHPC[k]>CHP2.NHPC[k]||CHP2.Av[k]!=1)&&Q[k][3]>Zero&&CHP1.NHPC[k]>StVal[k]/StVary[k]&&StVary[k]+0.5*(Tank.CR[k]-
HL[k])>Zero)
     if(StVary[k]+0.5*(Tank.CR[k]-HL[k]-Q[k][7])<-Zero)
                    { Q[k][3]-=2.0*StVary[k]+Tank.CR[k]-HL[k];
                     Tank.CR[k]-=2.0*StVary[k]+Tank.CR[k]-HL[k];
                     Q[k][7]=Q[k][2]+Tank.CR[k]+CHP1.RH[k]+CHP2.RH[k]-Q[k][3]-Q[k][5];
                    }
   if((CHP2.NHPC[k]>CHP1.NHPC[k]||CHP1.Av[k]!=1)&&Q[k][5]>Zero&&CHP2.NHPC[k]>StVal[k]/StVary[k]&&(StVary[k]+0.5*(Tank.CR[k]-HL[k]-
Q[k][5])>Zero))
     {Tank.CR[k]-=Q[k][5];Q[k][5]=0.0;}
   else if((CHP2.NHPC[k]>CHP1.NHPC[k]||CHP1.Av[k]!=1)&&Q[k][5]>Zero&&CHP2.NHPC[k]>StVal[k]/StVary[k]&&StVary[k]+0.5*(Tank.CR[k]-
HL[k])>Zero)
     if(StVary[k]+0.5*(Tank.CR[k]-HL[k]-Q[k][7])<-Zero)
                    { Q[k][5]-=2.0*StVary[k]+Tank.CR[k]-HL[k];
                     Tank.CR[k]-=2.0*StVary[k]+Tank.CR[k]-HL[k];
                     Q[k][7]=Q[k][2]+Tank.CR[k]+CHP1.RH[k]+CHP2.RH[k]-Q[k][3]-Q[k][5];
                    }
 }

//Correct the store level and losses through to end of day.
 for(int K=k;K<48;K++)
  { if(K<47){StVary[K+1]=StVary[K]+0.5*(Tank.CR[K]-HL[K]);
     StVal[K+1]=StVal[K]+0.5*(Tank.CR[K]*Tank.CRNHPC[K]-HL[K]*StVal[K]/StVary[K]);
     StVaryTemp[K+1]=StVary[K+1];HL[K+1]=HL_0*Tank.Cap+HL_c*StVary[K+1];}
    if(K==47){SDE=StVary[47]+0.5*(Tank.CR[47]-HL[47]);SDETemp=SDE;
     SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
  }
   }

 float HighDAHL,LowDAHL,DACMaxHL,DAL2HL;//heat loss if store on high/low trajectory
 HighDAHL=0;LowDAHL=0;DACMaxHL=0;SumDAL=0;SumDAL2=0;SumDACMin=0;
 SumDACMax=0;SumDAC2Max=0;SumDAG=0;SDEMax=Tank.Cap;SDEMin=0;
 if(P4==1&&Tank.Cap>Zero&&day<364)
  {  //PART 4: set limits on StoreDayEnd according to needs of next day.
    for(int n=0;n<48;n++)
     { if(DAQ[n][9]>Zero||DAQ[n][10]>Zero)SumDAL+=(DAQ[n][9]+DAQ[n][10])/2;
     if(CHP1.DAAv[n]==1&&DAQ[n][3]+Zero<CHP1.Min)SumDACMin+=CHP1.Min/2;
     if(CHP2.DAAv[n]==1&&DAQ[n][5]+Zero<CHP2.Min)SumDACMin+=CHP2.Min/2;
     if(CHP1.DAAv[n]==1&&DAQ[n][3]<CHP1.Max&&(DAQ[n][3]+Zero)>CHP1.Min)SumDACMax+=(CHP1.Max-DAQ[n][3])/2;//scope to charge
     if(CHP2.DAAv[n]==1&&DAQ[n][5]<CHP2.Max&&(DAQ[n][5]+Zero)>CHP2.Min)SumDAC2Max+=(CHP2.Max-DAQ[n][5])/2;//scope to charge
     if(DAQ[n][7]>Zero)SumDAG+=DAQ[n][7]/2;//scope to discharge

     if(SumDAG-(SumDAL+SumDACMin-HighDAHL)<0)HighDAHL+=(HL_0*Tank.Cap+HL_c*(SDEMax+SumDAL+SumDACMin-HighDAHL-
SumDAG))/2;
```

```
    if(SumDAG-(SumDAL+SumDACMin-LowDAHL)>SumDACMax)LowDAHL+=(HL_0*Tank.Cap+HL_c*(SDEMin+SumDAL+SumDACMin-LowDAHL-
SumDAG))/2;
    DACMaxHL+=HL_c*SumDACMax/2;
    //DACMax can be added (with increased heat losses) if that is how Min and Max converge

    //set store (current) day end limits...
    if(SumDAG<SumDAL+SumDACMin-HighDAHL)
                {if(SDEMax>Tank.Cap-(SumDAL+SumDACMin-HighDAHL-SumDAG))
                  if(SDEMin<Tank.Cap-(SumDAL+SumDACMin-HighDAHL-SumDAG))
                  SDEMax=Tank.Cap-(SumDAL+SumDACMin-HighDAHL-SumDAG);
                }
    //heat losses from DACMax+DAL2 only materialise, in addition to LowDAHL, if it is implemented
    if(SumDAG>SumDAL+SumDACMin-HighDAHL)//mainly days w DAG>HighCharge
                {if(SDEMin<SumDAG-SumDAL-SumDACMin+HighDAHL)
                  {if(SDEMax>SumDAG-SumDAL-SumDACMin+HighDAHL)
                        SDEMin=SumDAG-SumDAL-SumDACMin+HighDAHL;
                  }
                }
    if(SumDAG>SumDAL+SumDACMin+SumDACMax-LowDAHL-DACMaxHL)//mainly days w DAG>HighCharge
                {if(SDEMin<SumDAG-SumDAL-SumDACMin-SumDACMax+LowDAHL+DACMaxHL)
                  {if(SDEMax>SumDAG-SumDAL-SumDACMin-SumDACMax+LowDAHL+DACMaxHL)
                        SDEMin=SumDAG-SumDAL-SumDACMin-SumDACMax+LowDAHL+DACMaxHL;
                  }
                }
   }

   //PART4A:charge store if not meeting final value
    for(int k=47;P4==1&&k+1>0&&SDEMin-SDE>Zero;k--)
                { HeadRoom=Tank.Cap;//resets for each k, necessary?
                  if(k==47)HeadRoom=Tank.Cap-SDE;
                  for(int q=k+1;q<48;q++)//figure the HeadRoom available later
                    if(Tank.Cap-StVary[q]<HeadRoom)HeadRoom=Tank.Cap-StVary[q];
                  if(Tank.Cap-SDE<HeadRoom)HeadRoom=Tank.Cap-SDE;

NHPCCalc(CHP1.NHPC[k],CHP1.Av[k],Q[k][3],CHP1.Max,CHP1.R100,RVal,Price[k],ERF(Q[k][3],CHP1.Av[k]),ERF(Q[k][3]+dCHP,CHP1.Av[k]),dCHP);
NHPCCalc(CHP2.NHPC[k],CHP2.Av[k],Q[k][5],CHP2.Max,CHP2.R100,RVal,Price[k],BM(Q[k][5],CHP2.Av[k]),BM(Q[k][5]+dCHP,CHP2.Av[k]),dCHP);

   if(CHP1.NHPC[k]<CHP2.NHPC[k]-Zero&&CHP1.Av[k]==1&&0.5*(CHP1.Max-Q[k][3])<(SDEMin-SDE)&&0.5*(CHP1.Max-Q[k][3])<HeadRoom)
     {Tank.CR[k]+=CHP1.Max-Q[k][3];Q[k][3]=CHP1.Max;}//if space, full pelt
   else if(CHP1.NHPC[k]<CHP2.NHPC[k]-Zero&&CHP1.Av[k]==1&&0.5*(CHP1.Max-Q[k][3])>(SDEMin-SDE)&&(SDEMin-SDE)<HeadRoom)
     {Tank.CR[k]+=2*(SDEMin-SDE);Q[k][3]+=2*(SDEMin-SDE);}

   if(CHP2.NHPC[k]<CHP1.NHPC[k]-Zero&&CHP2.Av[k]==1&&0.5*(CHP2.Max-Q[k][5])<(SDEMin-SDE)&&0.5*(CHP2.Max-Q[k][5])<HeadRoom)
     {Tank.CR[k]+=CHP2.Max-Q[k][5];Q[k][5]=CHP2.Max;}//if space, full pelt
   else if(CHP2.NHPC[k]<CHP1.NHPC[k]-Zero&&CHP2.Av[k]==1&&0.5*(CHP2.Max-Q[k][5])>(SDEMin-SDE)&&(SDEMin-SDE)<HeadRoom)
     {Tank.CR[k]+=2*(SDEMin-SDE);Q[k][5]+=2*(SDEMin-SDE);}

   for(int q=k;q<48;q++)
     { HL[q]=HL_0*Tank.Cap+HL_c*StVary[q];
                if(q<47){StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                  StVal[q+1]=StVal[q]+0.5*(Tank.CR[q]*Tank.CRNHPC[q]-HL[q]*StVal[q]/StVary[q]);}
                if(q<47&&Tank.Cap-StVary[q+1]<HeadRoom)HeadRoom=Tank.Cap-StVary[q+1];//added <47
                if(q==47){SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                  SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
    }
                }
   //PART 4B:discharge store if headroom not achieved.
    for(int r=47;P4==1&&SDE-SDEMax>Zero&&r+1>0;r--)//added CR
                {  //FootRoom=Tank.Cap;
                  if(r==47){FootRoom=SDE;if(StVary[r]<FootRoom)FootRoom=StVary[r];}
                  for(int q=r+1;q<48;q++)//WAS r+1 figure HR available later
```

```
                        if(StVary[q]<FootRoom)FootRoom=StVary[q];
                       if(SDE<FootRoom)FootRoom=SDE;

NHPCCalc(CHP1.NHPC[r],CHP1.Av[r],Q[r][3],CHP1.Max,CHP1.R100,RVal,Price[r],ERF(Q[r][3],CHP1.Av[r]),ERF(Q[r][3]+dCHP,CHP1.Av[r]),dCHP);
NHPCCalc(CHP2.NHPC[r],CHP2.Av[r],Q[r][5],CHP2.Max,CHP2.R100,RVal,Price[r],BM(Q[r][5],CHP2.Av[r]),BM(Q[r][5]+dCHP,CHP2.Av[r]),dCHP);

                      if(CHP1.NHPC[r]>CHP2.NHPC[r]&&Q[r][3]>CHP1.Min+Zero)//reduce CHP to min or by amount required late in day
                      { if(SDE-SDEMax>0.5*(Q[r][3]-CHP1.Min)&&0.5*(Q[r][3]-CHP1.Min)<FootRoom)
                          {Tank.CR[r]-=Q[r][3]-CHP1.Min;Q[r][3]=CHP1.Min;}
                        else if(SDE-SDEMax>0.5*(Q[r][3]-CHP1.Min)&&0.5*(Q[r][3]-CHP1.Min)>FootRoom)
                          {Tank.CR[r]-=2.0*FootRoom;Q[r][3]-=2.0*FootRoom;}
                      }
                      if(CHP2.NHPC[r]>CHP1.NHPC[r]&&Q[r][5]>CHP2.Min+Zero)//reduce CHP to min or by amount required late in day
                      { if(SDE-SDEMax>0.5*(Q[r][5]-CHP2.Min)&&0.5*(Q[r][5]-CHP2.Min)<FootRoom)
                          {Tank.CR[r]-=Q[r][5]-CHP2.Min;Q[r][5]=CHP2.Min;}
                        else if(SDE-SDEMax>0.5*(Q[r][5]-CHP2.Min)&&0.5*(Q[r][5]-CHP2.Min)>FootRoom)
                          {Tank.CR[r]-=2.0*FootRoom;Q[r][5]-=2.0*FootRoom;}
                      }
                     for(int q=r;q<48;q++)
                      { HL[q]=HL_0*Tank.Cap+HL_c*StVary[q];
                        if(q<47){StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                          StVal[q+1]=StVal[q]+0.5*(Tank.CR[q]*Tank.CRNHPC[q]-HL[q]*StVal[q]/StVary[q]);}
                        if(q==47){SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                          SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
                      }
      }
   }//the PART 4 overall if(storecap>zero) loop

//PART 5A: increase CHP earlier reduce CHP later
  for(int k=47;P5a==1&&(Tank.Cap>0.5*CHP1.Min||Tank.Cap>0.5*CHP2.Min)&&k>=0;k--)//>49/0 to (de)activate
   { L=48;CRTemp[k]=0.0;
     for(int K=47;K>=0;K--)//calculates CHPLater for rest of day, exceeding CHPMin
       { CHPLater[K]=0;CHP2Later[K]=0.0;
                     if(K<47&&Q[K+1][3]>CHP1.Min+Zero)CHPLater[K]=CHPLater[K+1]+0.5*(Q[K+1][3]-CHP1.Min);
                     else if(K<47)CHPLater[K]=CHPLater[K+1];
                     if(K<47&&Q[K+1][5]>CHP2.Min+Zero)CHP2Later[K]=CHP2Later[K+1]+0.5*(Q[K+1][5]-CHP2.Min);
                     else if(K<47)CHP2Later[K]=CHP2Later[K+1];
                     if(Q[K][3]+Zero<CHP1.Min&&CHPLater[K]>0.5*CHP1.Min&&L==48&&CHP1.Av[K]==1)L=K;
                     if(Q[K][5]+Zero<CHP2.Min&&CHP2Later[K]>0.5*CHP2.Min&&L==48&&CHP2.Av[K]==1)L=K;
       }//L is the final period where CHP can be increased ahead of excess CHP

     //working through the CHP increase periods before CHP as k reduces void if out of store range
     if((L<48&&k<=L&&Q[k][3]+Zero<CHP1.Min&&CHP1.Av[k]==1)&&CHPLater[k]>0.5*CHP1.Min&&Tank.Cap>0.5*CHP1.Min)//+1
       { VoidLoop=0;VoidLoop2=0;StVaryTemp[k]=StVary[k];
                     SumCRT=0.0;J=48;CRTemp[k]=CHP1.Min-Q[k][3];//set a CRT[k] for period k, ready to tweak

                     if(k<47)StVaryTemp[k+1]=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                     if(k==47)SDETemp=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                     SumCRT=0.5*CRTemp[k];

                     for(int l=k+1;(SumCRT>Zero&&l<J)&&(StVaryTemp[k+1]<Tank.Cap&&SDETemp<Tank.Cap);l++)
                      { CRTemp[l]=0.0;
                        if((Q[l][3]>CHP1.Min+Zero)&&SumCRT-0.5*(Q[l][3]-CHP1.Min)>Zero)CRTemp[l]=-(Q[l][3]-CHP1.Min);
                        else if(Q[l][3]>CHP1.Min+Zero){CRTemp[l]=-2.0*SumCRT;J=l;}//finish loop
                       SumCRT+=0.5*CRTemp[l];

                      if(l<47)StVaryTemp[l+1]=StVaryTemp[l]+0.5*(Tank.CR[l]-HL[l]+CRTemp[l]);
                      if(l==47)SDETemp=StVaryTemp[47]+0.5*(Tank.CR[47]-HL[47]+CRTemp[47]);

                      if(l<47&&((StVaryTemp[l+1]-Tank.Cap)>Zero||StVaryTemp[l+1]<-Zero))VoidLoop=1;
                      if(l==47&&((SDETemp-SDEMax)>Zero||SDETemp<-Zero))VoidLoop2=1;
```

```
                    if((SumCRT<Zero&&J==l)&&(VoidLoop==0&&VoidLoop2==0))//success on charge->discharge.
                    { Tank.CR[k]+=CRTemp[k];//if charge then discharge success.
                      Q[k][7]=0;Q[k][3]=Q[k][2]-(Q[k][5]-CHP1.RH[k])-Q[k][7]+Tank.CR[k];
                      StVary[k+1]=StVaryTemp[k+1];
                    for(int q=k+1;q<=J;q++)
                      { Tank.CR[q]+=CRTemp[q];
                        Q[q][3]=Q[q][2]-(Q[q][5]-CHP1.RH[q])-Q[q][7]+Tank.CR[q];CRTemp[q]=0.0;
                        if(q<47){StVary[q+1]=StVaryTemp[q+1];
                                    StVal[q+1]=StVal[q]+0.5*(Tank.CR[q]*Tank.CRNHPC[q]-HL[q]*StVal[q]/StVary[q]);}
                        if(q==47){SDE=SDETemp;
                        SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
                      }
                    }
                    }//end of loop with l++
 for(int q=k;q<48;q++)
                  { if(q<47){StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                                    StVal[q+1]=StVal[q]+0.5*(Tank.CR[q]*Tank.CRNHPC[q]-HL[q]*StVal[q]/StVary[q]);}
                   if(q==47){SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                        SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
                  }
 }
if((L<48&&k<=L&&Q[k][5]+Zero<CHP2.Min&&CHP2.Av[k]==1)&&CHP2Later[k]>0.5*CHP2.Min&&Tank.Cap>0.5*CHP2.Min)//+1
 { VoidLoop=0;VoidLoop2=0;StVaryTemp[k]=StVary[k];
                   SumCRT=0.0;J=48;CRTemp[k]=CHP1.Min-Q[k][5];//set a CRT[k] for period k, ready to tweak

                   if(k<47)StVaryTemp[k+1]=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                   if(k==47)SDETemp=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                   SumCRT=0.5*CRTemp[k];

                   for(int l=k+1;(SumCRT>Zero&&l<J)&&(StVaryTemp[k+1]<Tank.Cap&&SDETemp<Tank.Cap);l++)
                     { CRTemp[l]=0.0;
                      if((Q[l][5]>CHP2.Min+Zero)&&SumCRT-0.5*(Q[l][5]-CHP2.Min)>Zero)CRTemp[l]=-(Q[l][5]-CHP2.Min);
                      else if(Q[l][5]>CHP2.Min+Zero){CRTemp[l]=-2.0*SumCRT;J=l;}//finish loop
                     SumCRT+=0.5*CRTemp[l];

                    if(l<47)StVaryTemp[l+1]=StVaryTemp[l]+0.5*(Tank.CR[l]-HL[l]+CRTemp[l]);
                    if(l==47)SDETemp=StVaryTemp[47]+0.5*(Tank.CR[47]-HL[47]+CRTemp[47]);

                    if(l<47&&((StVaryTemp[l+1]-Tank.Cap)>Zero||StVaryTemp[l+1]<-Zero))VoidLoop=1;
                    if(l==47&&((SDETemp-SDEMax)>Zero||SDETemp<-Zero))VoidLoop2=1;

                    if((SumCRT<Zero&&J==l)&&(VoidLoop==0&&VoidLoop2==0))//success on charge->discharge.
                    { Tank.CR[k]+=CRTemp[k];//if charge then discharge success.
                      Q[k][7]=0;
                      Q[k][5]=Q[k][2]-(Q[k][3]-CHP2.RH[k])-Q[k][7]+Tank.CR[k];
                      StVary[k+1]=StVaryTemp[k+1];
                    for(int q=k+1;q<=J;q++)
                      { Tank.CR[q]+=CRTemp[q];
                        Q[q][5]=Q[q][2]-(Q[q][3]-CHP2.RH[q])-Q[q][7]+Tank.CR[q];
                        CRTemp[q]=0.0;
                        if(q<47)StVary[q+1]=StVaryTemp[q+1];
                        if(q==47)SDE=SDETemp;
                      }
                    }
                    }//end of loop with l++
 for(int q=k;q<48;q++)
                  { if(q<47){StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                                    StVal[q+1]=StVal[q]+0.5*(Tank.CR[q]*Tank.CRNHPC[q]-HL[q]*StVal[q]/StVary[q]);}
                   if(q==47){SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                        SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
```

```
                        }
        }
    }

//PART 5B: reduce CHP earlier to increase CHP later
  for(int k=0;P5b==1&&(Tank.Cap>0.5*CHP1.Min||Tank.Cap>0.5*CHP2.Min)&&k<48;k++)
   { L=0;CRTemp[k]=0;
    for(int K=0;K<48;K++)//calculates CHPEarlier for earlier in day, exceeding CHPMin
      { CHPEarlier[K]=0.0;CHP2Earlier[K]=0.0;
                        StVaryTemp[K]=StVary[K];//new, removes any remnants of 5A StVary
                        if(K==47)SDETemp=SDE;//new
                        if(K>0&&Q[K-1][3]>CHP1.Min+Zero)
                          CHPEarlier[K]=CHPEarlier[K-1]+0.5*(Q[K-1][3]-CHP1.Min);
                        else if(K>0)CHPEarlier[K]=CHPEarlier[K-1];
                        if(K>0&&Q[K-1][5]>CHP2.Min+Zero)
                          CHP2Earlier[K]=CHP2Earlier[K-1]+0.5*(Q[K-1][5]-CHP2.Min);
                        else if(K>0)CHP2Earlier[K]=CHP2Earlier[K-1];
                        if(K>0&&Q[K][3]+Zero<CHP1.Min&&CHPEarlier[K]>0.5*(CHP1.Min-Q[K][7])&&CHP1.Av[K]==1&&L==0)L=K;
                        if(K>0&&Q[K][5]+Zero<CHP2.Min&&CHP2Earlier[K]>0.5*(CHP2.Min-Q[K][7])&&CHP2.Av[K]==1&&L==0)L=K;
                        //L is the first period where CHP can be increased after excess CHP
      }
    if(L>0&&k>=L&&Q[k][3]+Zero<CHP1.Min&&CHP1.Av[k]==1&&CHPEarlier[k]>0.5*(CHP1.Min-Q[k][7])&&Tank.Cap>0.5*CHP1.Min)
      { VoidLoop=0;
                        if(k<47)StVaryTemp[k+1]=StVary[k+1];else SDETemp=SDE;//added
                        SumCRT=0.0;J=0;CRTemp[k]=CHP1.Min-Q[k][7];//J=0 change from 48
                        //set a CRT[k] for period k, ready to tweak

                        if(k>0&&k<47)StVaryTemp[k]=StVaryTemp[k+1]-0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                        else if(k==47)StVaryTemp[k]=SDETemp-0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                        SumCRT=0.5*CRTemp[k];

                        for(int l=k-1;(SumCRT>Zero&&l>=0)&&(StVaryTemp[k]>Zero)&&J==0;l--)//was[k-1]and J==48
                          { CRTemp[l]=0.0;
                            if(Q[l][3]>CHP1.Min+Zero&&SumCRT-0.5*(Q[l][3]-CHP1.Min)>Zero)CRTemp[l]=-(Q[l][3]-CHP1.Min);
                            else if(Q[l][3]>CHP1.Min+Zero){CRTemp[l]=-2.0*SumCRT;J=l;}//finish loop

                           SumCRT+=0.5*CRTemp[l];
                           if(l<47)StVaryTemp[l]=StVaryTemp[l+1]-0.5*(Tank.CR[l]-HL[l]+CRTemp[l]);
                           if(l>0&&l<47&&StVaryTemp[l]<-Zero)VoidLoop=1;

                           if(SumCRT<Zero&&J==l&&VoidLoop==0)//success on discharge->charge. (SumCRT<Zero&&
                             { Tank.CR[k]+=CRTemp[k];//if charge->discharge success.
                                         StVary[k]=StVaryTemp[k];
                                         Q[k][7]=0;//added
                                         Q[k][3]=Q[k][2]-(Q[k][5]-CHP1.RH[k])-Q[k][7]+Tank.CR[k];

                                         for(int q=k-1;q>=J;q--)//changed to q=k+1 from q=k
                                           { Tank.CR[q]+=CRTemp[q];//more to less
                                             Q[q][3]=Q[q][2]-(Q[q][5]-CHP1.RH[q])-Q[q][7]+Tank.CR[q];
                                             CRTemp[q]=0.0;StVary[q+1]=StVaryTemp[q+1];//was q+1
                                           }
                             }
                          }//end of loop with l--
                        for(int q=k;q>=0;q--)//minus
                          { if(q<47){StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                                         StVal[q+1]=StVal[q]+0.5*(Tank.CR[q]*Tank.CRNHPC[q]-HL[q]*StVal[q]/StVary[q]);}
                            if(q==47){SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                              SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
                        }
      }
    if(L>0&&k>=L&&Q[k][5]+Zero<CHP2.Min&&CHP2.Av[k]==1&&CHP2Earlier[k]>0.5*(CHP2.Min-Q[k][7])&&Tank.Cap>0.5*CHP2.Min)
```

```
 { VoidLoop=0;
                    if(k<47)StVaryTemp[k+1]=StVary[k+1];else SDETemp=SDE;//added
                    SumCRT=0.0;J=0;CRTemp[k]=CHP2.Min-Q[k][7];//J=0 change from 48
                    //set a CRT[k] for period k, ready to tweak

                    if(k>0&&k<47)StVaryTemp[k]=StVaryTemp[k+1]-0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                    else if(k==47)StVaryTemp[k]=SDETemp-0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                    SumCRT=0.5*CRTemp[k];

                    for(int l=k-1;(SumCRT>Zero&&l>=0)&&(StVaryTemp[k]>Zero)&&J==0;l--)//was[k-1]and J==48
                      { CRTemp[l]=0.0;
                        if(Q[l][5]>CHP2.Min+Zero&&SumCRT-0.5*(Q[l][5]-CHP2.Min)>Zero)CRTemp[l]=-(Q[l][5]-CHP2.Min);
                        else if(Q[l][5]>CHP2.Min+Zero){CRTemp[l]=-2.0*SumCRT;J=l;}//finish loop

                       SumCRT+=0.5*CRTemp[l];
                       if(l<47)StVaryTemp[l]=StVaryTemp[l+1]-0.5*(Tank.CR[l]-HL[l]+CRTemp[l]);
                       if(l>0&&l<47&&StVaryTemp[l]<-Zero)VoidLoop=1;

                       if(SumCRT<Zero&&J==l&&VoidLoop==0)//success on discharge->charge. (SumCRT<Zero&&
                         { Tank.CR[k]+=CRTemp[k];//if charge->discharge success.
                                   StVary[k]=StVaryTemp[k];
                                   Q[k][7]=0;//added
                                   Q[k][5]=Q[k][2]-(Q[k][3]-CHP2.RH[k])-Q[k][7]+Tank.CR[k];

                                   for(int q=k-1;q>=J;q--)//changed to q=k+1 from q=k
                                     { Tank.CR[q]+=CRTemp[q];//more to less
                                       Q[q][5]=Q[q][2]-(Q[q][3]-CHP2.RH[q])-Q[q][7]+Tank.CR[q];
                                       CRTemp[q]=0.0;StVary[q+1]=StVaryTemp[q+1];//was q+1
                                     }
                         }
                      }//end of loop with l--
                    for(int q=k;q>=0;q--)//minus
                      { if(q<47){StVary[q+1]=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                                   StVal[q+1]=StVal[q]+0.5*(Tank.CR[q]*Tank.CRNHPC[q]-HL[q]*StVal[q]/StVary[q]);}
                        if(q==47){SDE=StVary[q]+0.5*(Tank.CR[q]-HL[q]);
                          SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
                    }
 }
 //Correct the store level and losses through to end of day.
 for(int K=k;K<48;K++)
  { if(K<47){StVary[K+1]=StVary[K]+0.5*(Tank.CR[K]-HL[K]);
                     StVal[K+1]=StVal[K]+0.5*(Tank.CR[K]*Tank.CRNHPC[K]-HL[K]*StVal[K]/StVary[K]);
                     StVaryTemp[K+1]=StVary[K+1];HL[K+1]=HL_0*Tank.Cap+HL_c*StVary[K+1];}
                    if(K==47){SDE=StVary[47]+0.5*(Tank.CR[47]-HL[47]);SDETemp=SDE;
                     SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
  }
}

//PART 6: remove residual LIWH by reducing CHP earlier noting store limits
 J=48;
 for(int k=47;P6==1&&Tank.Cap>Zero&&k>=1;k--)//was 0
  { L=48;
    CHP1.RHLater[47]=0.5*CHP1.RH[47];
     for(int K=47;K>=0;K--)
                   { CRTemp[K]=0;
                     if(K<47)CHP1.RHLater[K]=CHP1.RHLater[K+1]+0.5*(HL_c*CHP1.RHLater[K+1]+CHP1.RH[K]);
                    if(Q[K][3]>CHP1.Min+Zero&&CHP1.RHLater[K]>Zero&&L==48)L=K;
     }//L set as last period where CHP>Min before LIWH

     if(k<=L&&Q[k][3]>CHP1.Min+Zero&&L<48)
                   { StVaryTemp[k]=StVary[k];
```

```
                    if(CHP1.RHLater[k]>0.5*(Q[k][3]-CHP1.Min))CRTemp[k]=-(Q[k][3]-CHP1.Min);
                    else CRTemp[k]=-2*CHP1.RHLater[k];
                    SumCRT=0.5*CRTemp[k];
                    for(int l=k;SumCRT<-Zero&&l<48;l++)
                      { if(l>k)
                                   { HLTemp[l]=HL_c*SumCRT;
                                    if(SumCRT-0.5*HLTemp[l]+0.5*CHP1.RH[l]<Zero)
                                      {CRTemp[l]=CHP1.RH[l];SumCRT+=0.5*(CRTemp[l]-HLTemp[l]);}
                                    else {CRTemp[l]=-2.0*SumCRT;SumCRT=0;}//j=l removed end recharge
                                   }
                        if(l<47)StVaryTemp[l+1]=StVaryTemp[l]+0.5*(Tank.CR[l]+CRTemp[l]-HL[l]-HLTemp[l]);
                        if(l<47&&StVaryTemp[l+1]>Tank.Cap+Zero)
                                   {CRTemp[l]-=2.0*(StVaryTemp[l+1]-Tank.Cap);}
                        if(l<47&&StVaryTemp[l+1]<-Zero)//temp sto out limits
                                   {if(2.0*StVaryTemp[l+1]>CRTemp[k]*pow(1-0.5*HL_c,l-k))
                                      {CRTemp[k]-=2.0*StVaryTemp[l+1]*pow(1-0.5*HL_c,l-k);
                                       SumCRT=0.5*CRTemp[k];l=k;}
                                    else {CRTemp[k]=0;l=48;}
                                   }
                      }
                    Tank.CR[k]+=CRTemp[k];//change here

                    if(CRTemp[k]<-Zero)Q[k][3]=Q[k][2]-(Q[k][5]-(CHP1.RH[k]+CHP2.RH[k]))-Q[k][7]+Tank.CR[k];//added minus
                    for(int q=k+1;q<48&&CRTemp[k]<-Zero;q++)
                      { HL[q]+=HLTemp[q];
                        if(CRTemp[q]>Zero){Tank.CR[q]+=CRTemp[q];CHP1.RH[q]-=CRTemp[q];}
                        Q[q][3]=Q[q][2]-(Q[q][5]-(CHP1.RH[q]+CHP2.RH[q]))-Q[q][7]+Tank.CR[q];//k->q
                    }
                    for(int i=k;i<48&&CRTemp[k]<-Zero;i++)
                      {CRTemp[i]=0.0;StVary[i]=StVaryTemp[i];}
                   }//end of conditional
  }

for(int n=0;n<48;n++)
  {HL[n]=HL_0*Tank.Cap+HL_c*StVary[n];
   if(n<47){StVary[n+1]=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
                    StVal[n+1]=StVal[n]+0.5*(Tank.CR[n]*Tank.CRNHPC[n]-HL[n]*StVal[n]/StVary[n]);
                    StVaryTemp[n+1]=StVary[n+1];HL[n+1]=HL_0*Tank.Cap+HL_c*StVary[n+1];}
   if(n==47){SDE=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
     SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
  }

//PART 7: increase LIWH2 uptake earlier reduce gas later (acts at latest time)
L=48;J=48;
for(int k=47;P7==1&&Tank.Cap>Zero&&k>=0;k--)
  { CRTemp[k]=0.0;
   for(int K=47;K>k;K--)//calculates GasLater, was K>0
     { if(K==47)GB.HLater[K]=0.5*Q[K][7];
                    else GB.HLater[K]=GB.HLater[K+1]+0.5*(HL_c*GB.HLater[K+1]+Q[K][7]);
                    if(CHP2.RH[K]>Zero&&GB.HLater[K]>Zero&&L==48)L=K-1;
                    //L= final period where LHS2 can be reduced ahead of gas use
                    HLTemp[K]=0;
     }
    //working through the LHS2 reduce periods before Gas as k reduces
   if(L<47&&k<=L&&CHP2.RH[k]>Zero&&GB.HLater[k+1]>Zero)//+1
     { VoidLoop=0;StVaryTemp[k]=StVary[k];SumCRT=0;J=48;
                    //set a CRT[k] for period k, ready to tweak
                    if(GB.HLater[k+1]>0.5*CHP2.RH[k])CRTemp[k]=CHP2.RH[k];
                    else if(GB.HLater[k+1]<0.5*CHP2.RH[k])CRTemp[k]=2*GB.HLater[k+1];
                    SumCRT=0.5*CRTemp[k];
                    for(int l=k;SumCRT>Zero&&l<J;l++)//J is the upper limit, intially 48
```

```
                          { if(l>k)
                            {CRTemp[l]=0.0;
                                          HLTemp[l]=HL_c*SumCRT;
                                          if(SumCRT-0.5*(HLTemp[l]+Q[l][4])>Zero)CRTemp[l]=-Q[l][7];
                                          else {CRTemp[l]=-2.0*SumCRT+HLTemp[l];J=l;}//finish loop
                                          SumCRT+=0.5*(CRTemp[l]-HLTemp[l]);
                            }
                          if(l<47)StVaryTemp[l+1]=StVaryTemp[l]+0.5*(Tank.CR[l]-HL[l]-HLTemp[l]+CRTemp[l]);
                          if(l<47&&((StVaryTemp[l+1]-Tank.Cap)>Zero||StVaryTemp[l+1]<-Zero))VoidLoop=1;

                          if(VoidLoop==1)
                            { if(StVaryTemp[l+1]-Tank.Cap>Zero)
                                          CRTemp[k]-=2.0*(StVaryTemp[l+1]-Tank.Cap)*pow(1-0.5*HL_c,l-k);
                                         if(StVaryTemp[l+1]<-Zero)
                                          CRTemp[k]-=2.0*StVaryTemp[l+1]*pow(1-0.5*HL_c,l-k);
                                         //store levels outside the boundaries will be recalculated after l=k
                                         if(k<47)StVaryTemp[k+1]=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                                         if(k<47)HLTemp[k+1]=HL_0*Tank.Cap+HL_c*StVaryTemp[k+1];
                                         if(k==47)SDETemp=StVaryTemp[k]+0.5*(Tank.CR[k]-HL[k]+CRTemp[k]);
                                         SumCRT=0.5*CRTemp[k];l=k;VoidLoop=0;
                            }
      if(SumCRT<Zero&&J==l)//success on charge then discharge.
                         { Tank.CR[k]+=CRTemp[k];CHP2.RH[k]-=CRTemp[k];Tank.CRNHPC[k]=0;
                           for(int q=k+1;q<J+1;q++)
                            { Tank.CR[q]+=CRTemp[q];
                                          if(CRTemp[q]<-Zero)Q[q][4]+=CRTemp[q];
                                          CRTemp[q]=0.0;StVary[q]=StVaryTemp[q];HL[q]+=HLTemp[q];
                                          if(q==48)SDE=SDETemp;
                            }
                          }
                          }//end of loop with l++
      }
  }
for(int n=0;n<48;n++)
  {HL[n]=HL_0*Tank.Cap+HL_c*StVary[n];
   if(n<47){StVary[n+1]=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
                         StVal[n+1]=StVal[n]+0.5*(Tank.CR[n]*Tank.CRNHPC[n]-HL[n]*StVal[n]/StVary[n]);
                         StVaryTemp[n+1]=StVary[n+1];HL[n+1]=HL_0*Tank.Cap+HL_c*StVary[n+1];}
   if(n==47){SDE=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
                         SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
  }

 //PART 8: Looking to rearrange production timing so that timing is optimised
 bool NowLoSCHi,LoSCHiNow,NowHi0Lo,Hi0LoNow;//low-storecap-high, high-0-low
 for(int w=0;Tank.Cap>Zero&&P8==1&&w<192;w++)//runs this many times to repeat optimisaton 96
  {
 for(int l=0;l<48;l++)
  { //NHPC calculation
NHPCCalc(CHP1.NHPC[l],CHP1.Av[l],Q[l][3],CHP1.Max,CHP1.R100,RVal,Price[l],ERF(Q[l][3],CHP1.Av[l]),ERF(Q[l][3]+dCHP,CHP1.Av[l]),dCHP);
NHPCCalc(CHP1.NHPCDown[l],CHP1.Av[l],Q[l][3],CHP1.Max,CHP1.R100,RVal,Price[l],ERF(Q[l][3],CHP1.Av[l]),ERF(Q[l][3]-dCHP,CHP1.Av[l]),-dCHP);
NHPCCalc(CHP2.NHPC[l],CHP2.Av[l],Q[l][5],CHP2.Max,CHP2.R100,RVal,Price[l],BM(Q[l][5],CHP2.Av[l]),BM(Q[l][5]+dCHP,CHP2.Av[l]),dCHP);
NHPCCalc(CHP2.NHPCDown[l],CHP2.Av[l],Q[l][5],CHP2.Max,CHP2.R100,RVal,Price[l],BM(Q[l][5],CHP2.Av[l]),BM(Q[l][5]-dCHP,CHP2.Av[l]),-dCHP);

 if(CHP1.Av[l]!=1&&CHP2.Av[l]==1){NowHi.CHP=2;NowLo.CHP=2;}
 if(CHP2.Av[l]!=1&&CHP1.Av[l]==1){NowHi.CHP=1;NowLo.CHP=1;}

 if(Q[l][7]>Zero){NowHi.Price=GB.NHPC[l];NowHi.t=l;NowHi.CHP=0;
   NowLo.t=l;NowLo.CHP=0;NowLo.Price=GB.NHPC[l];HPrice[l]=GB.NHPC[l];}
 else if(CHP1.NHPCDown[l]>CHP2.NHPCDown[l]+Zero&&CHP1.Av[l]==1&&Q[l][3]-dCHP>CHP1.Min)//added condition
   {NowHi.Price=CHP1.NHPCDown[l]+Zero;NowHi.t=l;NowHi.CHP=1;NowLo.t=l;HPrice[l]=CHP1.NHPC[l];
    if(CHP2.Av[l]==1&&Q[l][5]+dCHP<CHP2.Max){NowLo.CHP=2;NowLo.Price=CHP2.NHPC[l];}
```

```
    else {NowLo.CHP=1;NowLo.Price=CHP1.NHPC[l];}
   }
 else if(CHP2.NHPCDown[l]>CHP1.NHPCDown[l]+Zero&&CHP2.Av[l]==1&&Q[l][5]-dCHP>CHP2.Min)//added condition
   {NowHi.Price=CHP2.NHPCDown[l]+Zero;NowHi.t=l;NowHi.CHP=2;NowLo.t=l;HPrice[l]=CHP2.NHPC[l];
    if(CHP1.Av[l]==1&&Q[l][3]+dCHP<CHP1.Max){NowLo.CHP=1;NowLo.Price=CHP1.NHPC[l];}
    else {NowLo.CHP=2;NowLo.Price=CHP2.NHPC[l];}
   }
 Hi.Price=NowHi.Price;Hi.CHP=NowHi.CHP;Hi.t=NowHi.t;Lo.Price=NowLo.Price;Lo.CHP=NowLo.CHP;Lo.t=NowLo.t;

 //Find Higher/Lower PPs accessible later. PP=price period
 NowLoSCHi=0;NowHi0Lo=0;
 for(int k=l+1;(CHP1.Av[l]==1||CHP2.Av[l]==1)&&(NowLoSCHi==0||NowHi0Lo==0)&&k<48;k++)//loop stop if st->limit/k=48
   {
NHPCCalc(CHP1.NHPC[k],CHP1.Av[k],Q[k][3],CHP1.Max,CHP1.R100,RVal,Price[k],ERF(Q[k][3],CHP1.Av[k]),ERF(Q[k][3]+dCHP,CHP1.Av[k]),dCHP);
NHPCCalc(CHP1.NHPCDown[k],CHP1.Av[k],Q[k][3],CHP1.Max,CHP1.R100,RVal,Price[k],ERF(Q[k][3],CHP1.Av[k]),ERF(Q[k][3]-dCHP,CHP1.Av[k]),-
dCHP);
NHPCCalc(CHP2.NHPC[k],CHP2.Av[k],Q[k][5],CHP2.Max,CHP2.R100,RVal,Price[k],BM(Q[k][5],CHP2.Av[k]),BM(Q[k][5]+dCHP,CHP2.Av[k]),dCHP);
NHPCCalc(CHP2.NHPCDown[k],CHP2.Av[k],Q[k][5],CHP2.Max,CHP2.R100,RVal,Price[k],BM(Q[k][5],CHP2.Av[k]),BM(Q[k][5]-dCHP,CHP2.Av[k]),-
dCHP);

 if(StVary[k]+0.5*dCHP*pow(1-0.5*HL_c,k-l-1)>Tank.Cap)NowLoSCHi=1;//0->t=k can be high PP
 if(StVary[k]-0.5*dCHP*pow(1-0.5*HL_c,k-l-1)<0)NowHi0Lo=1;//0->t=k can be low PP
 //seek high price later
 if(NowLoSCHi==0)
   { if(Q[k][7]>dCHP&&GB.NHPC[k]*pow(1-0.5*HL_c,k-l)>Hi.Price){Hi.Price=GB.NHPC[k]*pow(1-0.5*HL_c,k-l);Hi.t=k;Hi.CHP=0;}
    if(CHP1.NHPCDown[k]>CHP2.NHPCDown[k]&&Q[k][3]>CHP1.Min+dCHP*pow(1-0.5*HL_c,k-l)&&(CHP1.NHPCDown[k]*pow(1-0.5*HL_c,k-
l)>Hi.Price&&CHP1.Av[k]==1))
      if((Q[l][3]+dCHP<CHP1.Max&&NowLo.CHP==1)||(Q[l][5]+dCHP<CHP2.Max&&NowLo.CHP==2))
                        {Hi.Price=CHP1.NHPCDown[k]*pow(1-0.5*HL_c,k-l);Hi.t=k;Hi.CHP=1;}
    if(CHP2.NHPCDown[k]>CHP1.NHPCDown[k]&&Q[k][5]>CHP2.Min+dCHP*pow(1-0.5*HL_c,k-l)&&(CHP2.NHPCDown[k]*pow(1-0.5*HL_c,k-
l)>Hi.Price&&CHP2.Av[k]==1))
      if((Q[l][5]+dCHP<CHP2.Max&&NowLo.CHP==2)||(Q[l][3]+dCHP<CHP1.Max&&NowLo.CHP==1))
                        {Hi.Price=CHP2.NHPCDown[k]*pow(1-0.5*HL_c,k-l);Hi.t=k;Hi.CHP=2;}
   }
 //seek low price later
 if(NowHi0Lo==0)
   {if((Q[l][3]>CHP1.Min+dCHP&&NowHi.CHP==1)||(Q[l][5]>CHP2.Min+dCHP&NowHi.CHP==2))
      if(CHP1.NHPC[k]<CHP2.NHPC[k]&&Q[k][3]+dCHP*pow(1-0.5*HL_c,k-l)<CHP1.Max&&(CHP1.NHPC[k]*pow(1-0.5*HL_c,l-
k)<Lo.Price&&CHP1.Av[k]==1))
                        {Lo.Price=CHP1.NHPC[k]*pow(1-0.5*HL_c,l-k);Lo.t=k;Lo.CHP=1;}
    if((Q[l][5]>CHP2.Min+dCHP&&NowHi.CHP==2)||(Q[l][3]>CHP1.Min+dCHP&&NowHi.CHP==1))
      if(CHP1.NHPC[k]>CHP2.NHPC[k]&&Q[k][5]+dCHP*pow(1-0.5*HL_c,k-l)<CHP2.Max&&(CHP2.NHPC[k]*pow(1-0.5*HL_c,l-
k)<Lo.Price&&CHP2.Av[k]==1))
                        {Lo.Price=CHP2.NHPC[k]*pow(1-0.5*HL_c,l-k);Lo.t=k;Lo.CHP=2;}
   }
      }
    //Find Higher/Lower PPs accessible earlier
    LoSCHiNow=0;Hi0LoNow=0;
    for(int k=l-1;(CHP1.Av[l]==1||CHP2.Av[l]==1)&&(LoSCHiNow==0||Hi0LoNow==0)&&k+1>0;k--)
      {
NHPCCalc(CHP1.NHPC[k],CHP1.Av[k],Q[k][3],CHP1.Max,CHP1.R100,RVal,Price[k],ERF(Q[k][3],CHP1.Av[k]),ERF(Q[k][3]+dCHP,CHP1.Av[k]),dCHP);
NHPCCalc(CHP1.NHPCDown[k],CHP1.Av[k],Q[k][3],CHP1.Max,CHP1.R100,RVal,Price[k],ERF(Q[k][3],CHP1.Av[k]),ERF(Q[k][3]-dCHP,CHP1.Av[k]),-
dCHP);
NHPCCalc(CHP2.NHPC[k],CHP2.Av[k],Q[k][5],CHP2.Max,CHP2.R100,RVal,Price[k],BM(Q[k][5],CHP2.Av[k]),BM(Q[k][5]+dCHP,CHP2.Av[k]),dCHP);
NHPCCalc(CHP2.NHPCDown[k],CHP2.Av[k],Q[k][5],CHP2.Max,CHP2.R100,RVal,Price[k],BM(Q[k][5],CHP2.Av[k]),BM(Q[k][5]-dCHP,CHP2.Av[k]),-
dCHP);

 if(StVary[k+1]+0.5*dCHP>Tank.Cap)LoSCHiNow=1;
 if(StVary[k+1]-0.5*dCHP<0)Hi0LoNow=1;
 if(Hi0LoNow==0)
   if((CHP1.NHPCDown[k]*pow(1-0.5*HL_c,k-l)>Hi.Price&&CHP1.Av[k]==1)||(CHP2.NHPCDown[k]*pow(1-0.5*HL_c,k-l)>Hi.Price&&CHP2.Av[k]==1))
```

```
    { if((Q[l][3]<CHP1.Max-dCHP*pow(1-0.5*HL_c,l-k)&&NowLo.CHP==1)||(Q[l][5]<CHP2.Max-dCHP*pow(1-0.5*HL_c,l-k)&&NowLo.CHP==2))
                    if(CHP1.NHPC[k]>CHP2.NHPC[k]&&Q[k][3]>CHP1.Min+dCHP&&(CHP1.NHPCDown[k]*pow(1-0.5*HL_c,k-
l)>Hi.Price&&CHP1.Av[k]==1))
                     {Hi.Price=CHP1.NHPC[k]*pow(1-0.5*HL_c,k-l);Hi.t=k;Hi.CHP=1;}
                   if((Q[l][5]<CHP2.Max-dCHP*pow(1-0.5*HL_c,l-k)&&NowLo.CHP==2)||(Q[l][3]<CHP1.Max-dCHP*pow(1-0.5*HL_c,l-
k)&&NowLo.CHP==1))
                    if(CHP2.NHPC[k]>CHP1.NHPC[k]&&Q[k][5]>CHP2.Min+dCHP&&(CHP2.NHPCDown[k]*pow(1-0.5*HL_c,k-
l)>Hi.Price&&CHP2.Av[k]==1))
                     {Hi.Price=HPrice[k]*pow(1-0.5*HL_c,k-l);Hi.t=k;Hi.CHP=2;}
    }
 if(LoSCHiNow==0)
  if((CHP1.NHPC[k]*pow(1-0.5*HL_c,l-k)<Lo.Price&&CHP1.Av[k]==1)||(CHP2.NHPC[k]*pow(1-0.5*HL_c,l-k)<Lo.Price&&CHP2.Av[k]==1))
  {if(Q[l][7]>dCHP*pow(1-0.5*HL_c,l-k)||(Q[l][3]>CHP1.Min+dCHP*pow(1-0.5*HL_c,l-k)&&NowHi.CHP==1)||(Q[l][5]>CHP2.Min+dCHP*pow(1-
0.5*HL_c,l-k)&&NowHi.CHP==2))
    if(CHP1.NHPC[k]<CHP2.NHPC[k]&&Q[k][3]+dCHP<CHP1.Max&&(CHP1.NHPC[k]*pow(1-0.5*HL_c,l-k)<Lo.Price&&CHP1.Av[k]==1))
                   {Lo.Price=HPrice[k]*pow(1-0.5*HL_c,l-k);Lo.t=k;Lo.CHP=1;}
   if(Q[l][7]>dCHP*pow(1-0.5*HL_c,l-k)||(Q[l][5]>CHP2.Min+dCHP*pow(1-0.5*HL_c,l-k)&&NowHi.CHP==2)||(Q[l][3]>CHP1.Min+dCHP*pow(1-
0.5*HL_c,l-k)&&NowHi.CHP==1))
    if(CHP2.NHPC[k]<CHP1.NHPC[k]&&Q[k][5]+dCHP<CHP2.Max&&(CHP2.NHPC[k]*pow(1-0.5*HL_c,l-k)<Lo.Price&&CHP2.Av[k]==1))
                   {Lo.Price=HPrice[k]*pow(1-0.5*HL_c,l-k);Lo.t=k;Lo.CHP=2;}
  }
    }

   //Lo(Hi).t emerges as the lowest(highest) PP accessible by store movement
   //if more is gained by moving elec prod to high PP then do so, or vice versa
   //could repeat this if there is yet more to take off/add on currently
   //if(w==0&&day==185)cout<<"l: "<<l<<" Lo.t,CHP: "<<Lo.t<<","<<Lo.CHP<<" Hi.t,CHP: "<<Hi.t<<","<<Hi.CHP<<" Now Lo/Hi CHP:
"<<NowLo.CHP<<"/"<<NowHi.CHP<<endl;

   if(Hi.Price-HPrice[l]>HPrice[l]-Lo.Price&&Hi.t!=Lo.t&&Hi.t<l)
    {Tank.CR[Hi.t]-=dCHP;Tank.CR[l]+=dCHP*pow(1-0.5*HL_c,l-Hi.t);
                   if(Hi.CHP==0){Q[Hi.t][7]-=dCHP;Tank.CRNHPC[Hi.t]=GB.NHPC[Hi.t];}
                   if(Hi.CHP==1){Q[Hi.t][3]-=dCHP;Tank.CRNHPC[Hi.t]=CHP1.NHPCDown[Hi.t];}
                   if(Hi.CHP==2){Q[Hi.t][5]-=dCHP;Tank.CRNHPC[Hi.t]=CHP2.NHPCDown[Hi.t];}
                   if(NowLo.CHP==1){Tank.CRNHPC[l]=CHP1.NHPC[l];Q[l][3]+=dCHP*pow(1-0.5*HL_c,l-Hi.t);}
                   if(NowLo.CHP==2){Tank.CRNHPC[l]=CHP2.NHPC[l];Q[l][5]+=dCHP*pow(1-0.5*HL_c,l-Hi.t);}
    }
   if(Hi.Price-HPrice[l]>HPrice[l]-Lo.Price&&Hi.t!=Lo.t&&Hi.t>l)
    {Tank.CR[l]+=dCHP;Tank.CR[Hi.t]-=dCHP*pow(1-0.5*HL_c,Hi.t-l);
                   if(Hi.CHP==0){Q[Hi.t][7]-=dCHP*pow(1-0.5*HL_c,Hi.t-l);Tank.CRNHPC[Hi.t]=GB.NHPC[Hi.t];}
                   if(Hi.CHP==1){Q[Hi.t][3]-=dCHP*pow(1-0.5*HL_c,Hi.t-l);Tank.CRNHPC[Hi.t]=CHP1.NHPCDown[Hi.t];}
                   if(Hi.CHP==2){Q[Hi.t][5]-=dCHP*pow(1-0.5*HL_c,Hi.t-l);Tank.CRNHPC[Hi.t]=CHP2.NHPCDown[Hi.t];}
                   if(NowLo.CHP==1){Q[l][3]+=dCHP;Tank.CRNHPC[l]=CHP1.NHPC[l];}
                   if(NowLo.CHP==2){Q[l][5]+=dCHP;Tank.CRNHPC[l]=CHP2.NHPC[l];}
    }
   if(Hi.Price-HPrice[l]<HPrice[l]-Lo.Price&&Hi.t!=Lo.t&&Lo.t<l)
    {Tank.CR[Lo.t]+=dCHP;Tank.CR[l]-=dCHP*pow(1-0.5*HL_c,l-Lo.t);
                   if(Lo.CHP==1){Q[Lo.t][3]+=dCHP;Tank.CRNHPC[Lo.t]=CHP1.NHPC[Lo.t];}
                   if(Lo.CHP==2){Q[Lo.t][5]+=dCHP;Tank.CRNHPC[Lo.t]=CHP2.NHPC[Lo.t];}
                   if(NowHi.CHP==0){Q[l][7]-=dCHP*pow(1-0.5*HL_c,l-Lo.t);Tank.CRNHPC[l]=GB.NHPC[l];}
                   if(NowHi.CHP==1){Q[l][3]-=dCHP*pow(1-0.5*HL_c,l-Lo.t);Tank.CRNHPC[l]=CHP1.NHPCDown[l];}
                   if(NowHi.CHP==2){Q[l][5]-=dCHP*pow(1-0.5*HL_c,l-Lo.t);Tank.CRNHPC[l]=CHP2.NHPCDown[l];}
    }
   if(Hi.Price-HPrice[l]<HPrice[l]-Lo.Price&&Hi.t!=Lo.t&&Lo.t>l)
    {Tank.CR[l]-=dCHP;Tank.CR[Lo.t]+=dCHP*pow(1-0.5*HL_c,Lo.t-l);
                   if(Lo.CHP==1){Q[Lo.t][3]+=dCHP*pow(1-0.5*HL_c,Lo.t-l);Tank.CRNHPC[Lo.t]=CHP1.NHPCDown[Lo.t];}
                   if(Lo.CHP==2){Q[Lo.t][5]+=dCHP*pow(1-0.5*HL_c,Lo.t-l);Tank.CRNHPC[Lo.t]=CHP2.NHPCDown[Lo.t];}
                   if(NowHi.CHP==0){Q[l][7]-=dCHP;Tank.CRNHPC[l]=GB.NHPC[l];}
                   if(NowHi.CHP==1){Q[l][3]-=dCHP;Tank.CRNHPC[l]=CHP1.NHPCDown[l];}
                   if(NowHi.CHP==2){Q[l][5]-=dCHP;Tank.CRNHPC[l]=CHP2.NHPCDown[l];}
    }
```

```
    for(int n=0;n<48;n++)
      { HL[n]=HL_0*Tank.Cap+HL_c*StVary[n];
                            if(n<47){StVary[n+1]=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
                              StVal[n+1]=StVal[n]+0.5*(Tank.CR[n]*Tank.CRNHPC[n]-HL[n]*StVal[n]/StVary[n]);}
                            if(n==47){SDE=StVary[n]+0.5*(Tank.CR[n]-HL[n]);
                              SVDE=StVal[47]+0.5*(Tank.CR[47]*Tank.CRNHPC[47]-HL[47]*StVal[47]/StVary[47]);}
      }
  }
  }//repeats part 8

int SwitchCount,Switch2Count;
IntLHS1=0;IntLHS2=0;CHPHeatSales=0;CHP2HeatSales=0;GasHeatSales=0;IntDem=0;
CHPElecSales=0;CHP2ElecSales=0;SwitchCount=0;Switch2Count=0;
//PART 10: add the production up each day and add to the annual total
for(int k=0;k<48;k++)
  { CHPHeatSales+=Q[k][3]/2;CHP2HeatSales+=Q[k][5]/2;AnnLoss+=HL[k]/2;GasHeatSales+=Q[k][7]/2;
    IntLHS1+=CHP1.RH[k]/2;IntLHS2+=CHP2.RH[k]/2;IntDem+=Q[k][2]/2;
    Q[k][4]=ERF(Q[k][3],CHP1.Av[k]);Q[k][6]=BM(Q[k][5],CHP2.Av[k]);
    CHPElecSales+=Q[k][4]/2;ElecRev+=ElecRevenue(Price[k],Q[k][4])/2;
    CHP2ElecSales+=Q[k][6]/2;ElecRev2+=ElecRevenue(Price[k],Q[k][6])/2;

    if(k==0&&((CHPDayEnd<Zero&&Q[k][3]>Zero)||(CHPDayEnd>Zero&&Q[k][3]<Zero)))SwitchCount++;
    if(k>0&&((Q[k-1][3]<Zero&&Q[k][3]>Zero)||(Q[k-1][3]>Zero&&Q[k][3]<Zero)))SwitchCount++;
    if(k==0&&((CHP2DayEnd<Zero&&Q[k][5]>Zero)||(CHP2DayEnd>Zero&&Q[k][5]<Zero)))Switch2Count++;
    if(k>0&&((Q[k-1][5]<Zero&&Q[k][5]>Zero)||(Q[k-1][5]>Zero&&Q[k][5]<Zero)))Switch2Count++;
    if(k==47){CHPDayEnd=Q[k][3];CHP2DayEnd=Q[k][5];}


    float t;t=static_cast<float>((day-1)*24+k/2.0);
    //PRINT RESULTS:
    fout<<(day-1)*48+k<<"\t"<<t<<"\t"<<Q[k][2]<<"\t"<<Q[k][3]<<"\t"<<Q[k][4]<<"\t";
    fout<<Q[k][5]<<"\t"<<Q[k][6]<<"\t"<<Q[k][7]<<"\t"<<Price[k]<<"\t"<<CHP1.RH[k]<<"\t"<<CHP2.RH[k]<<"\t";
    fout<<StVary[k]<<"\t"<<Tank.CR[k]<<"\t"<<HL[k]<<"\t"<<Price[k]*Q[k][4]/2<<"\t"<<Price[k]*Q[k][6]/2<<endl;
  }

CHP1.AnnHSold+=CHPHeatSales;CHP2.AnnHSold+=CHP2HeatSales;
GB.AnnHSold+=GasHeatSales;CHP1.AnnPSold+=CHPElecSales;CHP2.AnnPSold+=CHP2ElecSales;
AnnDem+=IntDem;AnnSwitchCount+=SwitchCount;AnnSwitch2Count+=Switch2Count;

if(Tank.Cap>Zero){StDayStart=SDE;StValDayStart=SVDE;if(day==364){StYearEnd=SDE;StValYrEnd=SVDE;}} //for continuity of stored heat

}//day looping

CHP1.PEI=510000+GB.AnnHSold*(GasF1/100)/GB.Eff;//for QI Calculation
CHP2.PEI=800000+GB.AnnHSold*(1-GasF1/100)/GB.Eff;//tried 800 not 900, was 250000*13.25*1000.0/3600.0;
 TotalAnnualHeat=CHP1.AnnHSold+CHP2.AnnHSold+GB.AnnHSold;

 CHP1.QI=(CHP1.QI_e*CHP1.AnnPSold+CHP1.QI_t*(CHP1.AnnHSold+GB.AnnHSold*(GasF1/100)))/CHP1.PEI;
 CHP2.QI=(CHP2.QI_e*CHP2.AnnPSold+CHP2.QI_t*(CHP2.AnnHSold+GB.AnnHSold*(1-GasF1/100)))/CHP2.PEI;

 ROCRev=ROCRevenue(RVal,CHP1.QI,CHP1.R100,CHP1.R0,CHP1.AnnPSold);
 ROCRev2=ROCRevenue(RVal,CHP2.QI,CHP2.R100,CHP2.R0,CHP2.AnnPSold);

 if(GB.AnnHSold<Zero){GB.AnnHSold=0;}

 float M=1000000;//one million, to reduce some numbers below
 //List results for operator
 if(A==0)cout<<"Cap\tADem\tAHeat\tACHP1HS\tACHP1ES\tACHP2HS\tACHP2ES\tAGS\tER1-5.5\tER2-8.5\t";
 if(A==0)cout<<"QI1\tEff1\tQI2\tEff2\tRR1-6M\tRR2-18M\tALoss\tSwitch1\tSwitch2"<<endl;
 cout<<Tank.Cap<<"\t"<<AnnDem<<"\t"<<TotalAnnualHeat<<"\t"<<CHP1.AnnHSold<<"\t"<<CHP1.AnnPSold;
 cout<<"\t"<<CHP2.AnnHSold<<"\t"<<CHP2.AnnPSold<<"\t"<<GB.AnnHSold<<"\t"<<ElecRev-5.5*M<<"\t";
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  cout<<ElecRev2-8.5*M<<"\t"<<CHP1.QI<<"\t"<<CHP1.AnnPSold*100/CHP1.PEI<<"\t"<<CHP2.QI<<"\t";
  cout<<CHP2.AnnPSold*100/CHP2.PEI<<"\t"<<ROCRev-6*M<<"\t"<<ROCRev2-18*M<<"\t"<<AnnLoss<<"\t";
  cout<<AnnSwitchCount<<"\t"<<AnnSwitch2Count<<endl;
  fout.close();fin7.close();fin.close();fin2.close();fin3.close();
 }//A-Loop changes the store capacity

  return 0;
}

float ERF(float heat,int Avail)
{ float elec;
  if(Avail==1){elec=20.0;if(heat<18.0)elec=20.0-(4.8/18.0)*heat;
    if(heat>18.0&&heat<33.0)elec=15.2-(2.0/15.0)*(heat-18.0);
    if(heat>33.0)elec=13.2;}
  else elec=0;
  return elec;
}
float BM(float heat,int Avail)
{ float elec;
  if(Avail==1){elec=31.0;if(heat<25.0)elec=31.0-heat/6.0;
    if(heat>25.0)elec=31.0-25.0/6.0;}
  else elec=0;
  return elec;
}
float ElecRevenue(float Price,float PSold)
{ float Rev;Rev=Price*PSold;
  return Rev;
}
float ROCRevenue(float RVal,float QI,float ROC100,float ROC0,float PSold)
{ float Rev;
    if(QI>100)Rev=RVal*ROC100*PSold;
    else Rev=RVal*(ROC0+(ROC100-ROC0)*QI/100)*PSold;
    return Rev;
}
void NHPCCalc(float &NHPC,int Av,float now,float max,float R_100,float RVal,float Price,float Elec1,float Elec2,float dH)
{ if(Av==1&&now+dH<max)NHPC=(R_100*RVal+Price)*(Elec1-Elec2)/dH;
    else NHPC=100000;
  if(Av==1&&now+dH<0)NHPC=-10000;
}
```