Tyndall°Centre
for Climate Change Research

The potential for thermal storage to reduce the overall carbon emissions from district heating systems

Michael Martin & Dr Patricia Thornley

January 2013

Tyndall Centre for Climate Change Research

Working Paper 157

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The Tyndall Centre, Tyndall Manchester

Michael Martin - University of Manchester
michael.martin-2@manchester.ac.uk

Dr Patricia Thornley - University Manchester

Tyndall Working Paper 157, January 2013

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October 2012
Michael Martin & Dr Patricia Thornley
Tyndall Manchester
University of Manchester
Manchester M13 9PL
michael.martin-2@manchester.ac.uk

A research briefing funded by: Engineering and Physical Sciences Research Council

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Abbreviations

CCC	
CHP	Combined Heat and Power
CHPQA	CHP Quality Assurance programme
CHPA	Combined Heat and Power Association
DECC	Department of Energy and Climate Change
DH	District Heating
DHN	District Heating Network
DHS	Dynamic Heat Storage
DSM	Demand Side Management
EC	Energy Centre
EfW	Energy from Waste
ESCo	Energy Supply Company
MEF	Marginal Emissions Factor
PLC	Programme Logic Controller
SCaDA	Supervisory Control and Data Acquisition
SToD	Seasonal Time of Day

1. Introduction

1.1 Introduction to the District Heating Project

The study was compiled as part of an internship at the Tyndall Centre to investigate the techno-economic and policy aspects of district heating (DH) systems in the UK and although there were no direct industrial partners, extensive liaison took place with various persons involved in the promotion, operation and construction of DH systems.

1.2 Introduction to District Heating

District heating is a system for distributing heat generated from one or more sources via a network of insulated pipes carrying steam or hot water to heat buildings. The buildings can be residential and/or commercial with space heating and/or water heating requirements. The heat sources can be different types of power station such as industrial processing power plants which generate heat as a by-product, energy from waste (EfW) plant, heat-only boiler stations, geothermal or solar.

By utilising low grade heat which otherwise might have been wasted and displacing localised boilers DH systems can provide higher efficiencies and improve pollution control. DH can significantly contribute to achieving UK policy objectives in terms of:

- reducing primary energy supply and, consequently, import dependency
- reducing carbon dioxide emissions
- addressing fuel poverty

District Heating Networks (DHNs) provide a major opportunity for the deployment of combined heat and power (CHP) plants burning fossil fuels but increasingly biomass. Such “cogeneration” plants are designed to generate electricity whilst also capturing usable heat that is produced in this process. Their optimised design means that the overall efficiency of CHP plants can reach in excess of 80% at the point of use. Power plants, whether new build with heat take-off or retrofitted, are classified as CHP when connected to an operational DH system.

Whilst a DH development requires substantial initial investment to cover the construction of plant, heat network and connections, once operational, it provides a long term asset that enables a transition to a low-carbon energy system.

1.2.1 Utilisation of Waste Heat

DH can take low-grade heat from any source, and so can recycle “waste” heat streams that are difficult to use otherwise, and it permits seamless change to transporting renewable heat sources over time as new technologies become available.

Currently, large scale thermal and nuclear power stations in the UK waste as much as two thirds of the energy produced from the fuel they consume in the form of low grade heat dumped into the natural environment through cooling towers or flue gas or by cycling water from the sea or a river. A study by **AEA [2011-10,1]** for the Scottish Government examines the potential for new DHNs using heat recovery from large thermal power generation fitted with heat take off.

1.2.2 Reduction in Carbon Emissions

Whilst DH is expensive in the current commercial and policy environment, there is clear potential to save CO_2 as compared to conventional heating systems. In the past, DH in the UK was traditionally supplied with heat through the use of gas, oil or coal boilers **Parsons Brinkerhoff [2]** and whilst these systems provided economies of scale, the environmental benefits were limited to the greater overall operating efficiency of boilers servicing DHNs as compared with installations in individual dwellings or buildings. As the climate change imperative has permeated through into energy policy there is now a greater emphasis on using low-carbon fuels and more efficient plant as well as more rigorous energy performance standards for buildings. Consequently, the numbers of DHNs with CHP and/or biomass boilers are steadily growing in the UK resulting in substantial carbon savings and therefore contributing towards achieving building standards but without necessitating behaviour changes or actions by energy consumers.

Analysis by the **Claverton Energy Research Group [2007-02,3]** concludes that DH with CHP is the cheapest method of reducing carbon emissions, and has one of the lowest carbon footprints of all fossil generation plants. **Difs [2010,4]** identifies how a local energy company, producing DH and electricity in from CHP plants, can contribute to resource-efficient energy systems and cost-effective reductions of global CO_2 emissions.

The **Poyry Energy report [2009-04,5]** calculates that a DH network covering 250,000 households may save between 0.25 Mt CO2 and 1.25 Mt CO2 relative to conventional heating systems annually, dependent on the fuel used and the carbon intensity of centralised electricity production. Further analysis suggests that where DHNs can achieve a high penetration (in the region of 80%) in a built-up area, then carbon abatement costs of DH options can be better than the most cost-effective stand-alone renewable technology. The analysis shows that DHNs remain the preferred option for achieving carbon reduction in built-up areas unless electricity can be de-carbonised to a level below 0.15 tCO_2/MWh without raising its wholesale price above current levels (around £45/MWh).

A review of London’s energy policies published by the Greater London Authority (GLA) **[2011-10,6]** reported that CHP and DH infrastructure delivered the majority of London’s emissions savings in 2010 and have the greatest potential for future deployment.

1.2.3 Resource Efficiency

Where DH systems displace individual domestic or building heating installations, energy generation becomes more centralised and therefore it should be possible to make various savings:

- Plant within the end user connected buildings is reduced which should result in savings on maintenance costs and building space **[4]** since for DH installations only an interface unit between the DH system and customer heating systems is required.
- For non-domestic building connections, the interface unit occupies a significantly smaller space than the boiler required to meet the same heat demand which can free up lettable area.
- Energy centre plant can be regularly safety inspected and maintained without the administrative overhead of contacting building occupants or residents to arrange visits thereby avoiding lack of access problems.
- Overall reductions in maintenance labour time can also contribute to cost savings in administration.

1.2.4 Addressing Fuel Poverty

Between 4.0 and 5.5 million people in the UK live in fuel poverty – defined broadly as a situation where a household spends more than 10% of its income on fuel costs **(JRF,7)**. The ability of DH to deliver heat from high efficiency sources such as CHP or heat which otherwise would be lost can result in a lower unit cost of heat compared with alternative heat sources **[ParsonsBrinck,4]**. A proportion of this cost reduction can be passed through to the end user in the form of lower energy prices as is evidenced by the Lerwick and Aberdeen DH schemes. Also, the long term capital and maintenance cost for DH related pipework and equipment installed within networked buildings may often be lower than the individual installations they replace. Thus, depending on pricing policy, these economies can result in significant savings for the end-user and therefore contribute towards the alleviation of fuel-poverty. A number of authors have suggested that this will be relevant to consider in the future design of the DH regulatory regime.

1.2.5 Energy Security

A DHN distributes and delivers heat and, once installed and commissioned, can remain operational for decades with only routine maintenance. Also, a DHN is not sensitive to the plant that supplies the heat and therefore a succession of heating sources can be installed, operated and then replaced when they become life expired or obsolete. This flexibility helps create policy and regulation stability thereby helping to protect both the operator and consumers against fluctuations in market conditions and resource availability.

Heat from technologies currently in development, such as the hydrogen fuel cell or oxy-burn hybrid, or not yet publically acceptable, such as heat from nuclear power stations, may also supply heat to DHNs in years to come thus contributing towards the ‘future proofing’ of the DHN.

The countervailing argument is that customers could become “locked into DH” because they no longer have their own independent boiler and therefore are unable to access possible cost reductions which might be available from switching supplier.

1.2.6 Geopolitical security of supply

Geopolitical security of supply relates to the price volatility of fossil fuels, as well as the risk of supply interruptions to imported sources. With over 95% of heat in the UK is currently produced by burning fossil fuel but with North Sea supplies now in decline leading to an increase in imports the question of fuel security is sharply posed. These concerns create a significant additional rationale for improved energy efficiency and the development of electricity generation capacity such as renewables and nuclear which are not dependent on volatile fossil fuels. DH can play a crucial role by enabling the delivery of heat from renewable sources and waste streams.

1.2.7 Technical security of supply

Technical security of supply relates to the degree of certainty that energy supply will be available immediately when consumers want it. Analysis initiated via the Committee on Climate Change **[i]** suggests that technical security of supply can be maintained even with high penetrations of intermittent renewable electricity such as wind, alongside significant investment in relatively inflexible plant such as nuclear.

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[i] The Committee on Climate Change (CCC) is an independent body established under the Climate Change Act (2008). The CCC advises the UK Government on setting and meeting carbon budgets and on preparing for the impacts of climate change – see: http://www.theccc.org.uk/

Electricity based measures to ensure technical security of supply include investment in smart grids, peaking plant and interconnection with other European countries. Potential heat based measures could use CHP and DH has the potential to reduce peak electricity demands and provide a thermal ‘buffer’ to help manage the matching of electricity demand and supply CHPA [2010-02,8].

1.3 District Heating in the UK

Due to historical and structural reasons **[Russel, 2011-10,9]** penetration of DH in the UK is low with only around 4% of UK buildings currently connected to DHNs and a total installed capacity of CHP 5,569MWe **[10]** . By comparison, DH provides 14% of heat demand in Germany, 50% in Finland and 60% in Denmark **[Euroheat and Power,11].**

Studies have assessed the potential for DHNs to provide approximately 20% of UK heat demand. Both the UK and devolved governments have recognised the need to address this deficit and have gone some way to shifting policy in favour of DH systems. This is reflected in a recent study **[12]** by the Combined Heat and Power Association (CHPA) which has identified over 200 existing heat networks – a mixture of residential, commercial and public sites **[13]** - with a further 70 in development. The same study anticipates that the number of dwellings connected to DHNs will double within five years.

1.4 District Heating with Thermal Storage

CHP plant tends to be sized to average annual heat demand of the system to mitigate against plant oversizing and therefore If there is high demand for heat then peak load boilers might be brought into operation. For CHP-DH systems there can be circumstances where there is demand for electricity but insufficient demand for heat from networked customers and therefore CHP plant has to be turned off or surplus heat rejected to atmosphere. Both circumstances can be inefficient in terms of the fuel costs and carbon emissions which could potentially be avoided. Moreover, if too much heat is rejected then the “CHP quality” could be reduced to the point where the scheme no longer qualifies for revenue from Renewables Obligation Certificates (in the case of renewable fuel operation) or Climate Change Levy exemption (in the case of natural gas fuel). Good Quality CHP refers to CHP generation that is energy efficient in operation as determined via the CHP Quality Assurance programme administered by DECC **[ii]**.

If the CHP has been correctly matched to the system heat demand, then the alternatives to heat dumping are either to switch off the CHP and thereby lose revenue from electricity sales or to store the surplus heat for later use in an appropriately sized thermal store. In this study the term thermal store is used rather than heat accumulator although both terms are equally valid.

Thermal storage has been used with DHNs for more than two decades, for example, in Denmark, large-scale thermal store systems have been deployed to take advantage of liberalised electricity market and now almost all DH systems with CHP plant include heat storage. Just over 7% of the operational DH schemes in the UK of are known to operate with a thermal store **[14]**; however, as more schemes are developed and existing schemes are expanded, heat storage as a means to optimise performance is expected to become more widespread.

[ii] The Combined Heat and Power Quality Assurance (CHPQA) programme is administered by DECC, with the aim of improving the quality of CHP schemes. The CHPQA assessment is based on the energy efficiency and environmental performance of CHP plant compared to good alternative energy supply options – see: http://chpqa.decc.gov.uk/assets/Uploads/SummaryNov00.pdf

There are studies which describe the improved optimisation of DH systems made possible with thermal storage in terms of greater viability as a result of increased revenue from electricity sales.

Some studies mention the scope for emissions reductions as a result of storing heat which otherwise would have been dumped or by producing more electricity which reduces utilisation of less efficient grid based fossil fuel plant. However, there has been no systematic analysis of the potential for reduced emissions from DH schemes through the use of thermal storage in the UK context.

1.5 The scope, structure and purpose of the study

This study will examine the potential for thermal storage to improve the performance of DH systems in the UK using the reduction of the overall carbon emissions of the system as the main criterion. Results will be presented from the modelling of an existing CHP-DH system both with and without thermal storage with the objective of demonstrating whether thermal storage can lead to greater carbon reductions.

The energyPRO software has been used for the modelling and analysis of the CHP DH test system. A recent comparison **[15]** of the features of available energy modelling software identified energyPRO as a powerful and flexible application allowing the user to carry out a comprehensive, integrated and detailed technical and financial analysis of cogeneration systems.

The purpose of this study is to evaluate the potential for thermal storage to reduce the overall carbon emissions from DH systems in the UK and identify barriers to retrofitting existing schemes with thermal stores. The study contextualises the subject in the introduction with a discussion of the background in section 2 followed by a description of thermal stores and how they complement a DH network in section 3 with a summary of the extent of take up of thermal stores in section 4. Section 5 describes the methodology used in calculating the carbon savings from DH systems with and without thermal stores. Section 6 covers the results derived from the methodology and emulations of a CHP-DH test case using the energyPRO modelling programme. Section 7 consists of a discourse on the results and section 8 the conclusions.

2. Background

A study by the IEA **[2005,16]** analyses data from real DH-systems in Denmark, Germany and Finland to determine advantages of dynamic heat storage (DHS) optimization techniques for DH systems. The results show that for DH systems with CHP, DHS can increase the scope for electricity production, leading to significant balance sheet improvements and carbon emissions savings. For DHNs both with and without electricity production, DHS can be used to store heat to cover for a supply interruption to a contracted fuel source, e.g. waste for an EfW plant, rather than use a heat only boiler with more expensive fuel bought in via a speculative market. Looked at another way, heat stores facilitate demand side management (DSM) so that the operator can exercise greater choice in relation to plant utilisation and fuel sources.

The IEA study **[2005,17]** lays out reasons for installing centralised or decentralised thermal stores in district heating or cooling systems which include:

- To eliminate bottlenecks in heat production
- To eliminate bottlenecks within the distribution network
- To reduce peak load unit operation
- To improve utilisation of waste heat or base load units

- To enable time shift of heat versus electricity utilisation in the case of CHP
- To enhance revenues by taking advantage of time variable energy prices
- To replace the normal heat production during shorter planned or unplanned production stops

The main priority is normally to produce and distribute the energy in the most cost efficient way. In the case of CHP the store is used to shift the electricity production in time to maximize the production to timeslots with high electricity price. The excess heat produced during these periods is stored and used when the electricity price is low. It should be emphasised that many operators will opt to have electricity purchasing agreements with constant diurnal tariffs which only change according to the time of year and thereby obviate the need for more complex operational strategies or give rise to more predictable income stream.

A further IEA study **[2008,18]** demonstrates improved economic viability of cogeneration in small DHNs with thermal storage and explores long-term storage technologies and their cost by volume.

The Woods, and Turton study **[2010-06,19]** shows that the ‘Smart Heat Grid’ concept is worthy of further detailed evaluation in comparison with other forms of demand-side management and storage. There is the potential for DH projects to receive additional income in offering an electricity grid management capability both now and in the future.

A study by Haeseldonckx, Peeters, Helsen and D’haeseleer **[2005-06,20]** evaluates how thermal storage can lead to a significant reduction in overall CO_2 emissions by increasing the annual operational hours of building scale CHP. The study also shows how the performance of multiple small-scale CHP units can be aggregated into one large-scale, virtual CHP unit for the determination of the net reduction of CO_2 emissions from the Belgian power system.

The Fragaki, Andersen and Toke study **[2007-12,21]** analyses the economics and optimum size of CHP operating with gas engines and thermal stores in British market conditions using the **energyPRO** cogeneration analysis software. The study shows that the use of thermal stores could enable an operator of a CHP-DH system to take advantage of the Seasonal Time of Day (SToD) price structure typical of the UK to increase revenue from greater electricity sales. The CHP is worth running when the electricity price is high but if the heat demand is low (e.g. summer daytime), the excess heat is stored in the thermal store. The stored heat can then be used when the electricity demand, and therefore the electricity price, is low and it is not economical to run the CHP (e.g. night-time). In other cases, the heat stored when the production exceeds the demand can be used when the heat produced by the CHP is not enough to meet the heat load (e.g. winter). If there is no thermal store then, the gas engine has either to be sized to meet the minimum heat demand or should be stopped or modulated in order to avoid dumping the extra heat.

The study shows that the economical size of CHP plant for a DH load of 20,000MWh per year is a 3MWe gas engine with a 7.8MWh thermal store. In this case the analysis reveals that the use of a thermal store more than doubles the return on investments (as measured in net present value) compared with the same size of a plant without a thermal store. It is concluded that thermal stores can improve the overall economics of CHP plants in present British circumstances.

The Fragaki and Andersen study **[2010-07,22]** builds on their previous research to show that thermal stores could further improve the economics of CHP plants with direct access to the power exchange market via aggregated electricity dispatch. The study uses the Danish experience to demonstrate how CHP-DHNs with thermal stores are used to help balance electricity supply and demand where there is a significant proportion of variable capacity from wind farms. Since most CHP plants in the UK are small scale their operators avoid the expense of complying with the requirements of the Balancing and Settlement Code (BSC) and sell electricity to a third party at prices which are significantly lower than that paid to the owners of large scale plant.

The Kelly and Pollitt study **[2009-10,23]** uses a comparative approach to demonstrate the economic viability of CHP-DHNs in the UK based on the analysis of six operational CHP-DHNs, two of which – Woking and Barkantine - have thermal stores. The study describes how thermal stores can be used to store (low-value) heat for later use making it possible to produce power at times of peak (high-value) electricity demand thus maximising the revenue potential of electricity.

The Christidis, Koch, Pottel and Tsatsaronis study **[2010-09,24]** focuses on the potential for increasing profitability through the addition of thermal stores in the Berlin DH system, on the optimal storage capacities for different price scenarios (variation of fuel costs, prices for carbon dioxide emission certificates, and electricity price time series) as well as on the adjustment of the operation of the power plants due to heat storage. The study concludes that investments in heat storage which enable the partially decoupling of the heat produced by CHP plant from the heat demand from its DHN, have attractively short pay-back periods and significant overall carbon savings. However, at a sub-system level, the higher capacity utilization of gas-fired CHP plant can lead to an increase in greenhouse gas production although this is offset by increased electricity production. An important question here would be the marginal emissions factor (MEF) of the displaced electricity on the German grid but this is beyond the scope of this study.

3. Thermal stores

The only proven heat storage technology for use with CHP-DHNs is that of water in steel tanks which are normally cylindrical with volumes of up to ranging from 5m^3 for building scale CHP to 73,000m^3 **[25]**. The water content in the tank by volume is constant and independent of energy content. When charging the store, hot supply water is supplied in the top of the tank simultaneously with extraction of the same amount of cold return water from the bottom of the tank. The hot and cold water separate - due to difference in gravity - with an approximate 1 meter high non-usable separation layer. When discharged, hot supply water is extracted from the top with simultaneous supply of cold return water at the bottom.

The thermal store is connected to the district heating system between the CHP plant and the DH network as illustrated in **Fig. 1** below. The operation of the store is straightforward: it is charged when heat production is higher than the consumption, and discharged when heat production is below the consumption. This allows for the CHP plant to run more flexibly, in particular, when electricity prices are most favourable.

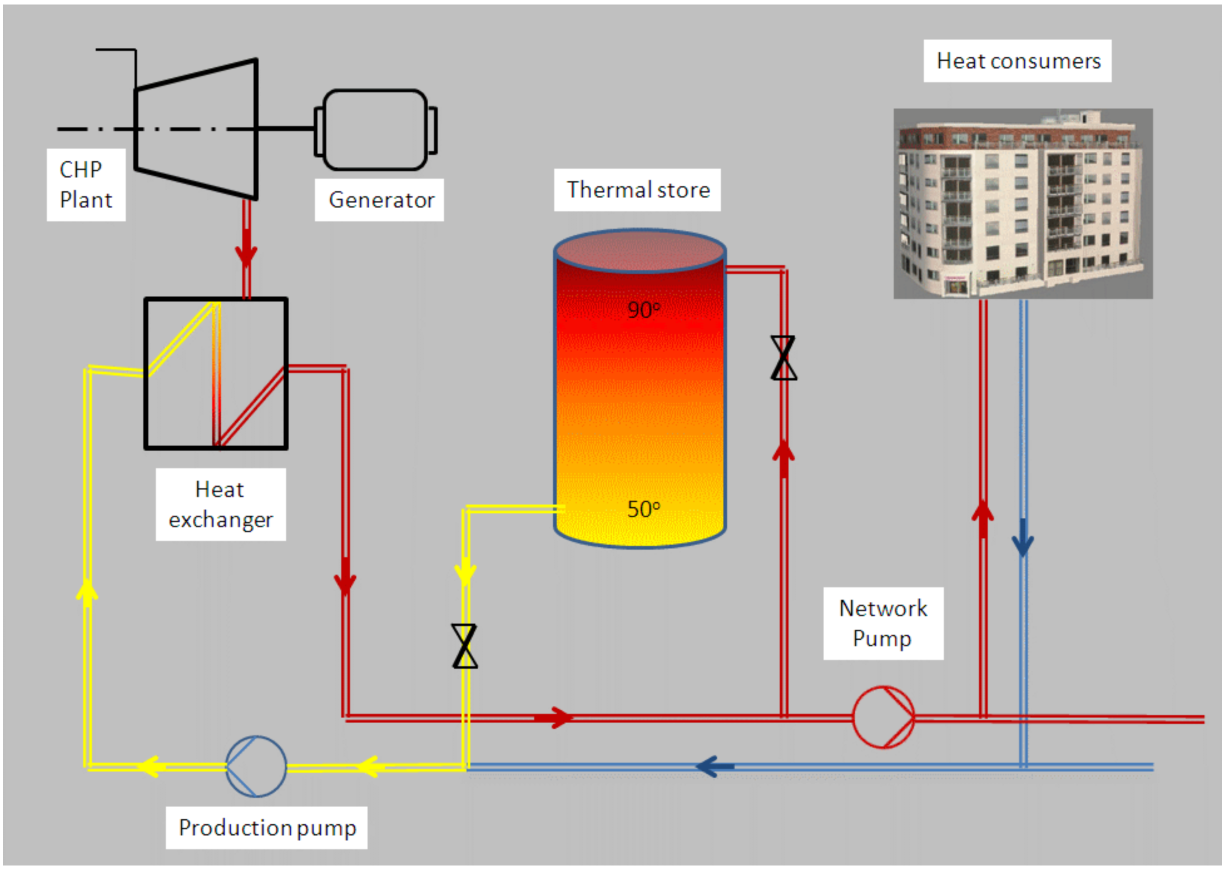

Fig. 1. Thermal store integrated in a DH system

The energy stored - or available – in water can be calculated as follows:

$E = c_p \, dt \, m$

Where:

E = energy (kJ)

c_p = specific heat capacity (4.2 kJ/kg°C for water)

dt = temperature difference between water stored and the surroundings (°C)

m = mass of water (kg)

Assuming a temperature difference between the supply and return of 40°C, an average density of 977kg/m^3 corresponding to 70°C, then E = 4.2*40*977kJ = 164,136kJ for 1m^3 of water.

Using a conversion of 1 Joule = 2.7778×10^{-7} kilowatt-hour gives an approximate figure of 22m^3 of water storage to supply 1MWh of thermal energy. This figure can be put into perspective by using the test case explored in this study which consists of a CHP-DH network supplying heat to almost 1,000 dwellings and an equivalent commercial customer base. The daily heat demand for the system varies from a low of 40MWh in summer to a high of 83MWh in winter with an average of 57MWh. The store would therefore need to have a volume of at least 1,250m^3 to cover an entire day's heat load, however, a store would normally be sized so as to maximise electricity revenue and minimise the payback period leading to a significantly smaller optimal volume.

3.1 Advantages of thermal stores

The inclusion of a thermal storage in a CHP-DH system potentially enables greater flexibility of operation and improved efficiency, more specifically an appropriately size store can:

a) Allow the CHP plant to produce heat and electricity in periods with the highest electricity prices. If there is surplus heat, this can be used to charge the thermal store. This mode of operation is especially important in grids with a tariff with time differentiation.

b) For large CHP-DH systems, the CHP plant can produce electricity until the store is fully charged during periods where there is a shortage of electricity on the grid, i.e. the store can assist with “grid-balancing” as is practised in Denmark where there is high but variable wind capacity.

c) Reduce or avoid income losses, for example, if electricity produced s liable to be sold below production costs, then the CHP plant may be turned off while heat is supplied to the system from the store. If the store is sufficiently large then CHP plant can be switched off over weekends, when the electricity price is often lower than on weekdays.

d) Compensate for the daily load variations in the heat demand, during the night for example, and thus reduce the number of CHP engine switch- ons and the use of boilers, in the daily peak load periods.

In principle the inclusion of a thermal store could permit the maximum capacity of the CHP plant to be reduced provided the combined heat output of the store and plant can meet demand on the “coldest day”. However, compared with the overall cost of a CHP-DH system such a reduction would provide only a marginal gain and potentially stymie future growth of the network as new customers are identified.

3.2 Thermal store design

Thermal stores are designed and fabricated by specialist companies e.g. Hoval, Ormandy, for a particular system and site requirement and so there are no sales catalogues for thermal stores larger than 5,000 litres, i.e. 5m^3, capacity. Thermal storage vessels are generally manufactured in accordance with the European Commission Pressure Equipment Directive PED/97/23/EC

Thermal stores are normally pressurised at the same level as the DH system but very large stores can be vented to atmosphere at the top as in the case of Pimlico, with the height of the water column in the store providing the static head to the DH network.

Vessels can have high or low height to diameter ratio and are designed to sit vertically or horizontally although vertical orientation is more common in DH systems due to space constraints and more preferable water stratification properties.

Vessels are manufactured for a particular operational pressure which has a direct bearing on the weight and is typically around 3 to 6 bar. The vessel is tested to a higher pressure according to the design code. The vessel body is rolled and pressed. The top and bottom of the vessel consists of semi-hemispherical heads which are pressed between two blocks and welded to the vessel body. Internally there are baffle plates to modulate water mixing and sparge pipes designed to achieve optimum circulation of water stored within the tank.

3.2.1 Corrosion protection

Since the tank is made principally from carbon steel it is important that the DH water quality meets requirements **[26]**, especially in relation to low oxygen content, to mitigate corrosion. Corrosion of the upper part of the shell and roof construction is avoided by maintaining an inactive atmosphere in the form of a steam or nitrogen cushion. It is good practice to drain the stores every few years for maintenance to, for example, examine welds and remove any sediment due to sludge.

3.2.2 Insulation

The standard insulation for stores consists of 100-300mm thick, compressed mineral wool which is expected to withstand temperatures up to 130°C. Other materials include polyurethane Insulation and cork. The amount of heat lost per annum from the store clearly depends on the insulation thickness and the ambient temperature and normally will be less than 0.1% of the total heat produced by the system plant.

3.2.3 Dimensioning

Most thermal stores are designed with a height/diameter ratio above 1.5 to minimize the volume of the inactive separation layer between the hot and cool volumes but also to reduce the spatial footprint of the store. However, a store can have a height/diameter ratio as low as 0.8 as in the case of the Odense store in Denmark.

The non-usable separation layer will typically have a thickness of one meter which limits the active storage volume. The temperature difference between the supply and return flows has a direct impact on the size of the tank and these are typically between 30 to 40 degrees for tanks at atmospheric pressure and can be higher for pressurised tanks.

3.3 Barriers to adoption

3.3.1 Inadequate control system

New build larger scale DH systems in the UK are being specified with thermal storage and intelligent Programme Logic Controller (PLC)-based Supervisory Control and Data Acquisition system (SCaDA) systems which allow monitoring of the system condition at different points and remote switching of plant and equipment to facilitate appropriate functioning. Using such a system enables the production of heat and electricity to be planned according to daily conditions and requirements taking into account the contents of the thermal store. Many of the existing CHP-DH systems rely on basic control systems and would have to be upgraded to make optimum use of a thermal store. This would require a significant investment depending on the particularities of the plant and system in addition to the capital cost of the thermal store. Training of personnel would also be required to make optimum use of the new control systems.

3.3.2 The pressurisation unit

The pressurisation unit may also need to be resized upwards due to the greater system volume when the store is connected.

3.3.3 Business as usual inertia

If a CHP-DH system is already performing satisfactorily then the additional investment required for thermal storage and related peripherals together with the disruption caused during the installation and the possibility that personnel might have to learn new ways of operating the plant may combine to deter the operators from upgrading **[27]**.

3.3.4 Cost

The cost for buying and installing a thermal store for units larger than 5m^3 are not listed in catalogues due to need for larger stores to be fabricated to fit a specific site and system.

According to industry sources the cost of thermal storage is approximately £1,000 per m^3 with associated instrumentation estimated to be approximately £3,500. Whilst it is difficult to generalise as to what additional control instrumentation might be necessary in specific retro-fit cases, a figure of £30-35,000 for a complete upgrade and refit would be typical. Thus the overall cost for a 200m^3 store and concomitant upgrade approaches £250,000 which could be paid back through additional electricity sales.

The 2007 Fragaki study **[28]** suggests a cost of £179,652 for a 252m^3 store with a three year pay-back period but without the additional instrumentation costs. Estimates for the test case below indicate a significantly longer pay-back period with the risk of extension in the event of volatile gas prices which would narrow the “spark-gap” between the sale price of the electricity and the cost of the gas fuel for the plant.

3.3.5 Space constraints and planning objections

Store larger than 100m^3 will typically have a diameter of 3.5 metres – the greatest diameter which can be transported by road without the expense of a police escort. The height of a store can be ten metres or more.

Thermal stores can also block light from nearby buildings and could be perceived as visually intrusive although this can be mitigated with, for example, wooden cladding, and in some European countries large scale municipal plant facades have been used for artistic purposes such as the Spittelau EfW facility in Vienna.

3.3.6 Lack of sufficient policy incentive

There are currently no policies in place which would incentivise DH operators to install thermal storage. Such policies might be VAT relief or a carbon tax.

4. Existing UK CHP-DH schemes with thermal storage

The recent survey by the CHPA has identified 15 DH schemes which have thermal stores and are either operational, in the process of being refurbished or under construction. The operators of several existing schemes are considering the addition of thermal storage to increase flexibility, reduce carbon emissions and increase revenue.

The Pimlico District Heating Undertaking (PDHU) first became operational in 1950 and initially relied on waste heat from the now-disused Battersea power station on the south side of the Thames. A new energy centre has recently been built which incorporates 3.1MWe/4MWth of gas-fired CHP engines and three 8MW gas-fired boilers. The thermal store was built in 1950s and, with a volume of 2300m^3, is the largest in the UK. Two thirds of the store volume is used for thermal storage with a capacity of 86MWh with the other third used as a cool store when necessary to maintain a suitable return temperature to the CHP plant. The store permits the operators to take advantage of favourable electricity tariffs via a power purchase agreement to sell directly to grid. The store is drained every ten years for maintenance which includes removing sediment and examining the welds on the plate steel although it is reported that they appear to have good longevity.

The Thameswey group have had experience with a 500m^3 thermal store connected in to their CHP-DH system at Milton Keynes. The store gives the flexibility to track electricity prices. Thameswey are also planning to retrofitting thermal storage to several smaller systems to reduce the frequency of power cycling.

There appears to be a consistent view based on both theory and practise that thermal stores confer benefits in terms of greater flexibility and increased electricity sales from CHP-DHNs. It is also the case that some operators are considering the addition of thermal storage on existing networks to achieve greater optimisation and also to be able to demonstrate greater carbon emissions reductions.

5. Methodology

The methodology for this work uses a whole life cycle approach to calculating the additional energy balance for a thermal store installation and then an equivalent carbon balance, which takes into account key greenhouse gas releases, primarily CO_2.

Four types of energy consumption have been considered for this process:

a) The energy used in production of the thermal store and associated installation such as additional control instrumentation. This is often referred to as “embodied energy”.

b) The energy consumed by the CHP plant and boilers to produce electricity and heat (Fchp).

c) The energy saved by not running individual domestic boilers (Fsve).

d) The electricity not drawn down from the grid due to the operation of the CHP plant both with and without thermal storage (Egrid).

Conversion factors were applied to the above energies to give an annual amount of carbon saved in terms of tons of CO_2 per annum expressed as follows:

$$\text{Csave} = (\text{Fsve}*\text{Cng}/\eta\text{boil} - \text{Fchp}*\text{Cng} + \text{Egrid}*\text{CIgrid})/1000 \qquad \text{(Equation 1)}$$

Where:

Cng = 0.198 = mass of CO_2 emitted per unit of energy from burning natural gas ($kgCO_2/kWh$)

ηboil = 0.85 = efficiency of domestic boilers

CIgrid = Grid Carbon Intensity ($kgCO_2/kWh$)

The grid carbon intensity has time dependent value according to the year.

The carbon emissions derived from the embodied energy of the store and associated installation was subtracted from the first year’s carbon savings.

The embedded carbon of a SCADA system and the larger sized pressurisation unit if an existing system has to be retro-fitted have not been taken into account due to time constraints. However, electronic systems can have very high embodied energy because of their specialist manufacture **[29]** and, depending on the layout of the site, cable runs and associated trays could be quite long i.e. more than 10m and even as long as100m.

5.1 Estimating embodied energy

The energy used in the production of the stores for a range of sizes from 73 to 115 m^3 was calculated using basic engineering drawings supplied by a design and installation company for DH systems **[30]** as per **Table 1** below. The key metrics were the weight of the store, thickness of insulation and cladding, types of material and fabrication operations such as welding.

The energy used in the production of the pipes servicing the store, associated valves, support struts and the concrete used for foundations of the store have also been taken into account – see appendix 1 for full breakdown. The amount of embodied carbon was calculated using standard methodologies available in the public domain **[31]**.The carbon steel pressure vessel accounts for the bulk of the total embodied carbon due to its weight of steel with the concrete base and other carbon steel items such as the pipework making up the rest as per **Table 2**. Estimates for the embodied carbon used in the analysis were obtained by interpolation as per **Table 3**.

Table 1 – Thermal store embodied carbon

Volume of store	m^3	74	73	115
Total Embodied Carbon	$kgCO_2$	55,689	80,884	88,561

Table 2 – Components of thermal store embodied carbon

Component	Percentage of whole
Pressure vessel including welding	88.31
Insulation and cladding	2.27
Pipes, valves and instrumentation	1.27
Support struts and concrete base	8.15

Table 3 – Estimated embodied carbon for the thermal store capacities used in the analysis

Capacity (m^3)	50	75	100	125	150	200
Embodied carbon (kg)	38,505	57,757	77,010	96,262	115,514	154,019

The steel pressure vessel must be able to withstand the pressure of the DH system which is typically between 3 to 6 bar and therefore it will inevitably account for a high proportion of the total embodied carbon. In some situations, for example where the DH network services an area built on hilly terrain, system pressure can exceed the level beyond the practical limits of vessel thickness which could support such a pressure. In this case it is necessary to install a heat exchanger between the DH system and the thermal store which would incur further expense and additional embodied carbon.

5.2 Estimating carbon emissions due to the operation of the DH system

Analysis has been performed using energyPRO on an existing CHP-DH scheme which does not have thermal storage using metrics which include fuel consumed, heat and electricity exported, heat dumped, CHP running times etc. The same energyPRO model was then run with appropriately sized thermal stores. Outputs from energyPRO include an environmental report which details the annual CO_2, NOx and SO_2 emissions from the plant.

Whilst a CHP-DH system will generally benefit from regular maintenance, there are heat losses from the system of pipes and electricity losses mainly due to pumping. These have been analysed by Woods and

Zdanuik **[32]** using figures obtained from the Danish District Heating Association which show a weighted average of 17% for heat losses and electricity use in the region of 0.2% to 0.7% of heat supplied for smaller DH schemes and a range 0.5% to 1.5% for larger schemes. The authors suggest that wide spread of results for heat losses probably reflects the range of heat densities supplied and the variation in age of the network.

No account has been taken of the carbon emissions incurred by the scheduled maintenance required for CHP plant, in particular, oil and filter changes, the use of flushing agents, etc.

5.3 Estimating the energy saved by not running individual domestic boilers

In the UK approximately 87% of domestic consumers corresponding to almost 21 million householders are connected to the mains gas grid **[2010-03,33]** many of whom have had decades of experience of individual boilers supplying both heat and hot water. Many of older boilers have been replaced with condensing boilers which can achieve over 90% efficiency **[34]**, however, the boiler, on start-up, has to reach optimum operational temperature and, in some cases, boilers have not been correctly matched to the heat load or have been poorly commissioned and therefore do not perform efficiently. In other cases householders are using older boilers which have lower nominal efficiencies although up to 7 million British households might be expected to benefit from boiler upgrades by 2020 **[HoC,ECC]**.

By comparison with DH schemes, building scale system reliant on heat only boilers will benefit from shorter pipe runs and less pumping losses.

Taking in account the above factors and the possibility of irregular maintenance a figure of 85% efficiency for domestic boiler has been used in the calculations.

5.4 Estimating carbon emissions saved from electricity not drawn down from the grid

The electricity produced from CHP-DH systems contributes significantly towards not only their financial viability but also the argument for supporting CHP as a low carbon energy source through the saving of higher carbon content electricity which otherwise would have been bought from the grid.

The CO_2 emissions saved by reducing the demand for electricity supplied via the grid is typically assessed by using an assumed grid emissions rate known as the “marginal emissions factor” (MEF). MEFs are higher than system average emission factors because the power stations that will be typically switched off in the short term (or not built in the long term) in response to a reduction in electricity demand are likely to be marginal plant such as coal fired power stations rather than hydro, wind or nuclear.

For those CHP-DH systems which are fuelled by natural gas as opposed to EfW or biomass, an accurate estimation as to which MEFs to use is crucial in determining to degree to which these systems have a comparative advantage in terms of emissions savings over competing forms of energy generation.

For this study, two scenarios for MEFs for UK national grid carbon intensity have been used to calculate the carbon saved by avoiding the consumption of grid electricity; the first is based on savings (marginal) emission factors posted by DECC **[35][36]** and the second on MEFs suggested in a study by Hawkes **[2010-03, 37]**. These are depicted in **Fig. 2** below.

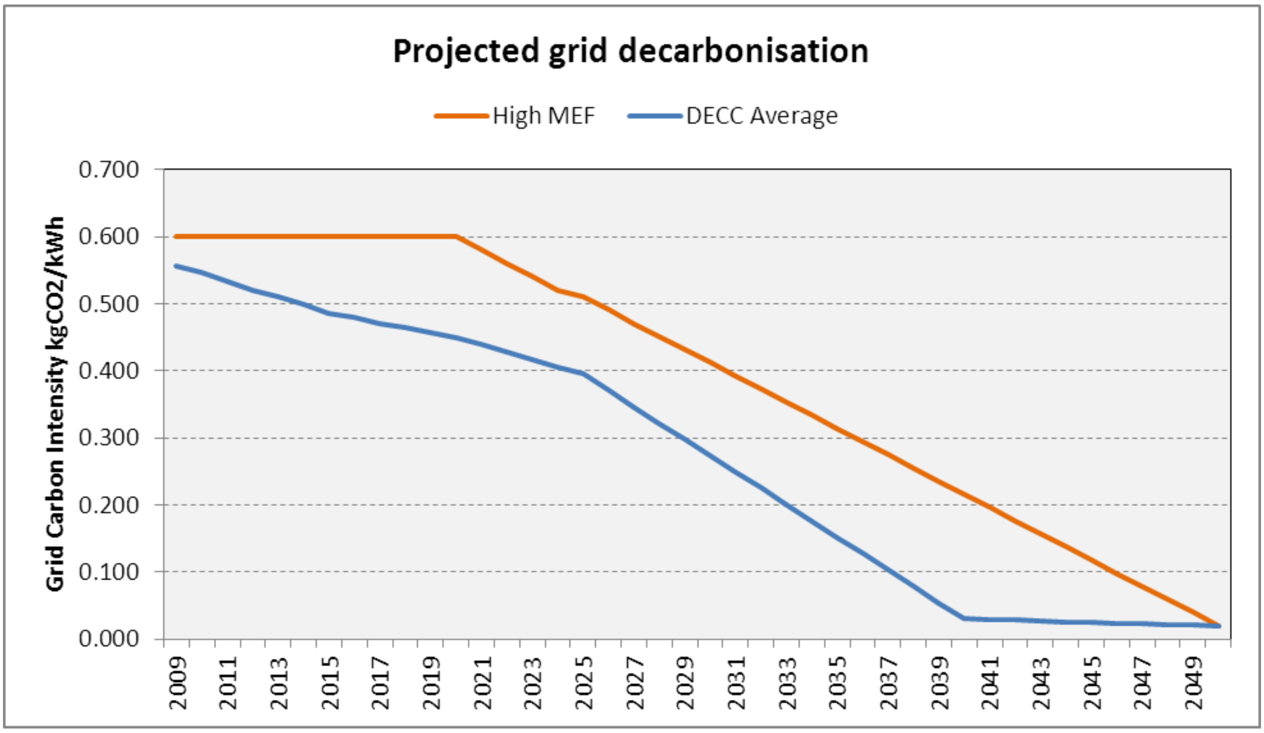

Fig. 2. Grid intensity projections

The Hawkes study presents an alternative formulation of the principles by which MEFs are estimated based on the observed behaviour of large power generators in response to demand change in the UK electricity system in the period 1st January 2002 to 31st December 2009. In contrast to previous methodologies, no assumptions are made in relation to dispatch following merit-order rules[iii]. Instead, linear regression coefficients of change in the system CO_2 rate versus change in total system demand are calculated to derive an estimated MEF of 0.69KgCO_2/kWh for this period with an error of +/-10%. The MEF was found to be sensitive to total system load and to vary according to the time of day between limits of approximately 0.35 and 0.77 KgCO_2/kWh. By replacing power stations scheduled for closure from the from the generation mix with new generators reflecting the MEFs of plant scheduled to be built in the near-term, a figure was obtained of 0.6KgCO_2/kWh for the decade 2010-20. The analysis was extended further but with increasing uncertainties, to derive a figure of 0.51 KgCO_2/kWh by 2025. Relevant charts from the Hawkes paper depicting 2002-2009 MEFs have been reproduced overleaf.

[iii] Merit order is defined as the order of dispatch according to cost of operation, with the underlying assumption that the cheapest generators are dispatched first, followed by more expensive systems, until system demand is met in a given time period (ibid).

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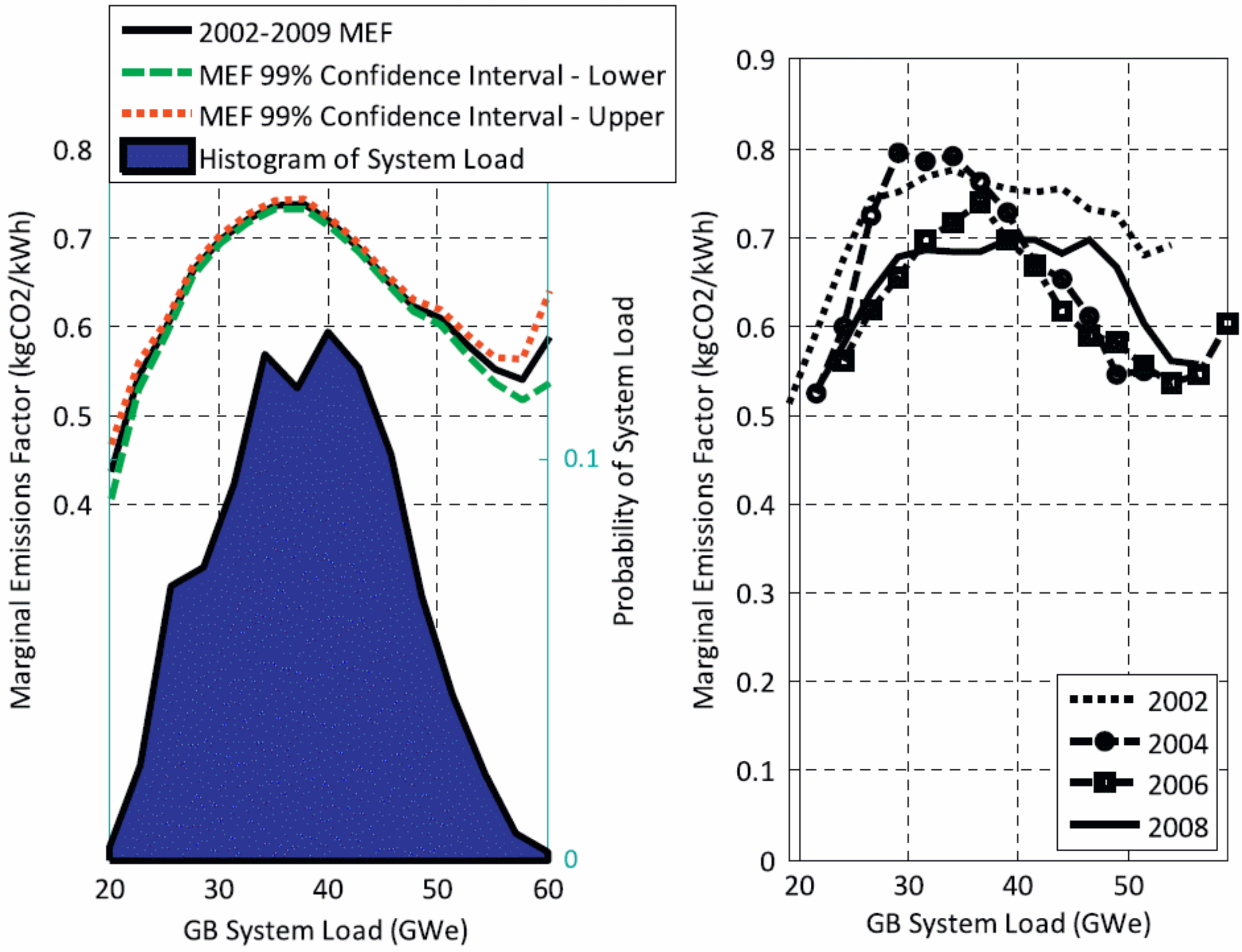


Fig. 4. Marginal emissions factor as a function of system load in Great Britain with corresponding confidence interval and Density of System Load (left) and by Year (right).

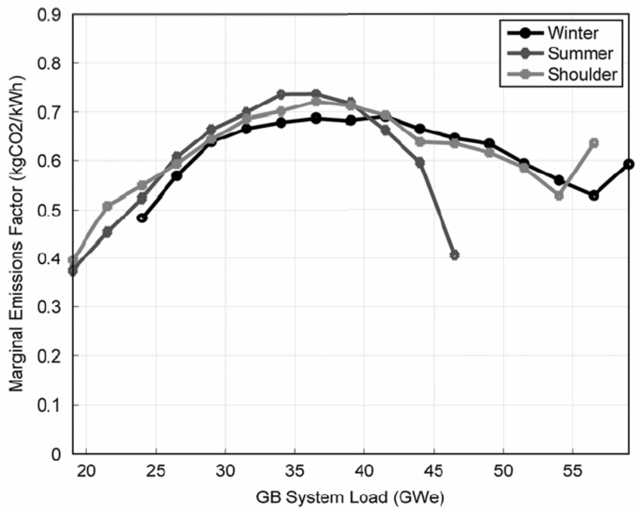


Fig. 5. Marginal emissions factor as a function of system load in Great Britain by season. Winter is November to February, Summer is May to August and "Shoulder" is September, October, March and April.

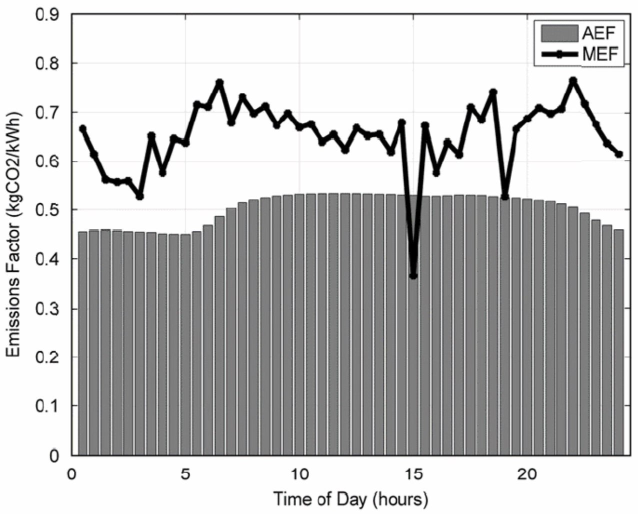


Fig. 6. Marginal emissions factor and average emissions factor as a function of Time of Use in Great Britain from 2002 to 2009.

5.5 The test case

The test case consists of an operational CHP-DH scheme in the UK with an annual heat demand of 18,116MWhrs supplied by two 1MWe CHP reciprocating gas engines, one boiler rated at 2MWh and three at 1MWh output as depicted in **Fig. 3** below. CHP plants of the reciprocating engine type – either spark ignition or compression ignition - are typical of UK CHP-DH systems. The modelling assumes there is a constant ratio between electricity and heat production as indicated by the manufacturer’s specification sheets. The annual heat demand is expected to rise to 21,030MWh/yr and therefore scenarios for both heat loads are included in the results. Where possible, data supplied by the operator has been used as input parameters for energyPRO.

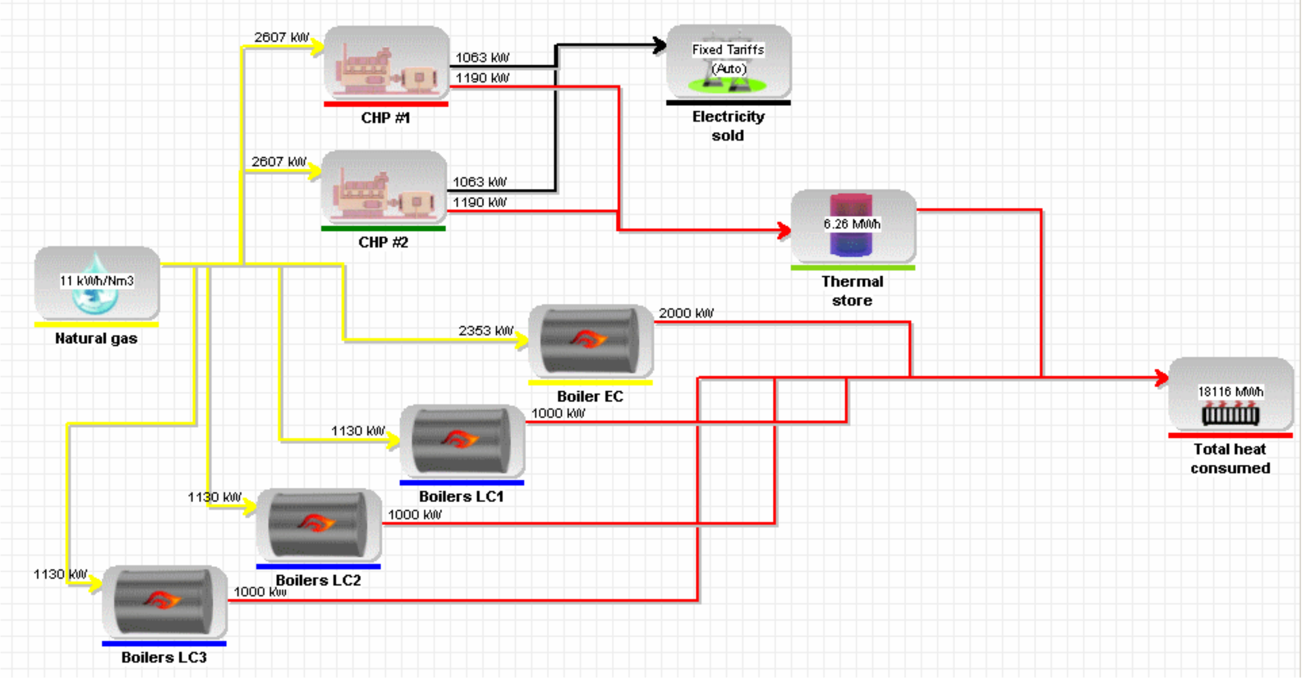


Fig. 3. CHP system configuration

5.6 energyPRO inputs

5.6.1 Modelling heat demand

Most CHP systems are heat led, in other words the heat demand from the system determines operational strategy. energyPRO permits the user to emulate the heat demand profile by setting parameters and inputting times series describing external conditions such as temperatures and wind speed. For the test case 70% of the demand was identified as dependent on external conditions which left 30% of demand as independent to reflect hot water demand and network losses. The dependent demand was restricted to the period from 1st September through to 31st May.

Daily outdoor mean temperatures and wind speeds pertaining to the test case locale were obtained from the US based National Center for Atmospheric Research (NCAR) reanalysis project **[38]** and the UK based Met Office **[39]**.

Heat demand for the test scheme varies systematically on a daily basis and this was modelled in energyPRO using the “Fixed profile demand” with the period 6am to 11pm set to maximum and other times to half-maximum.

5.6.2 Modelling the thermal store

Eight conditions for the system were modelled - without storage and with store sizes of 25, 50, 75, 100, 125, 150 and 200m^3. The store top and bottom temperatures were set to 90 and 50 degree respectively with utilisation set to 90%. Mineral wool with a thickness of 300mm was specified for the store insulation. An ambient temperature of 10 degrees was also specified although this could also be set to the outdoor temperature; in fact the difference in result between the two was insignificant.

5.6.3 Period of Examination

The life expectancy of a gas reciprocating engine is 15 to 20 years during which time it might be reasonable to expect that bio-fuels become more widely available and competitive with comparable fossil fuels. Therefore the plant management might decide to migrate to bio-fuel or part bio-fuel operation or to replace the plant itself by another type of heat source such as energy from waste, low grade heat from thermal or nuclear power stations, oxy-burn, etc. For the purposes of this study, it will be assumed that the engine will last 21 years, covering the period from 2014 to 2035 without migration to bio-fuels.

6. Results

The results from the energyPRO runs for the selected case study are depicted and explained below. The reference case is without thermal storage.

6.1 The carbon costs

Annual emissions savings were derived using equation (1) for both the reference case and with a 150m^3 store and plotted for both heat loads as per **Fig. 4** and **Fig. 5** overleaf. The embodied carbon for the thermal store was apportioned for the period 2014 to 2035 and thereupon deducted annually.

Fig. 4. Carbon emissions saved using DECC MEFs and MEFs for 18,112MWh/year heat load.

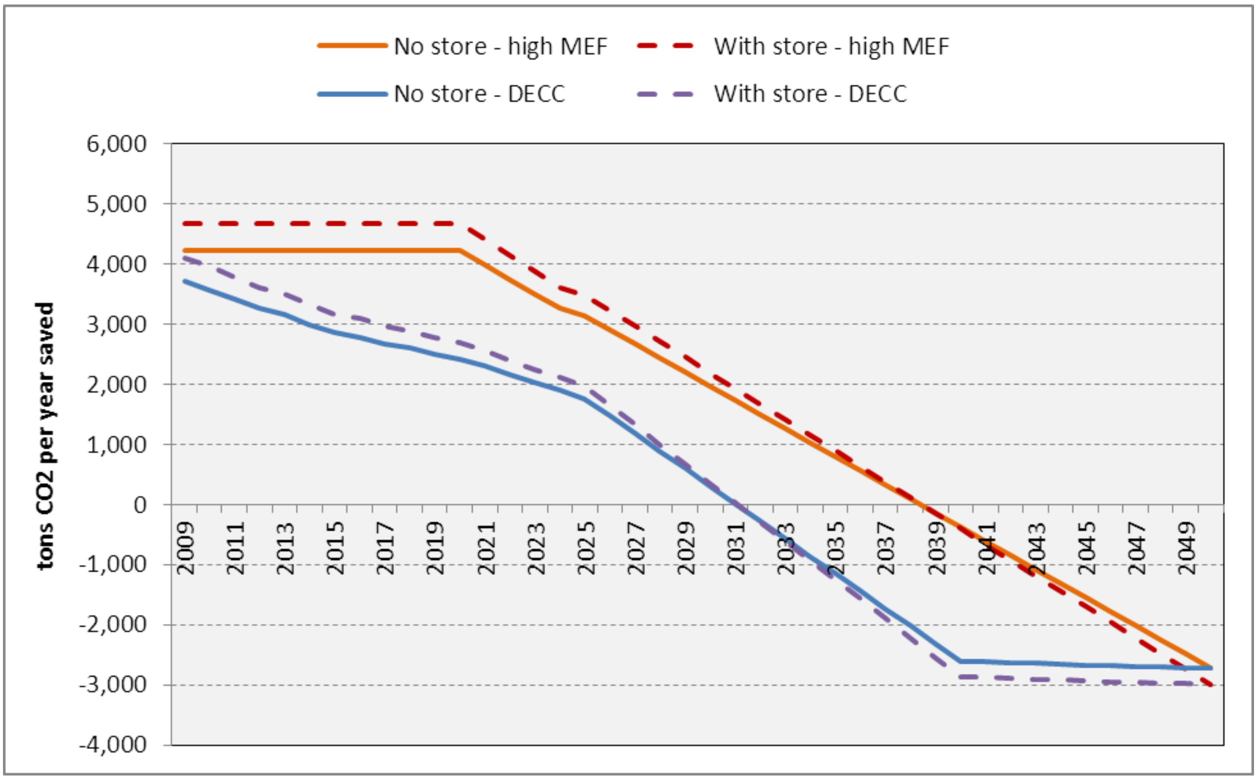
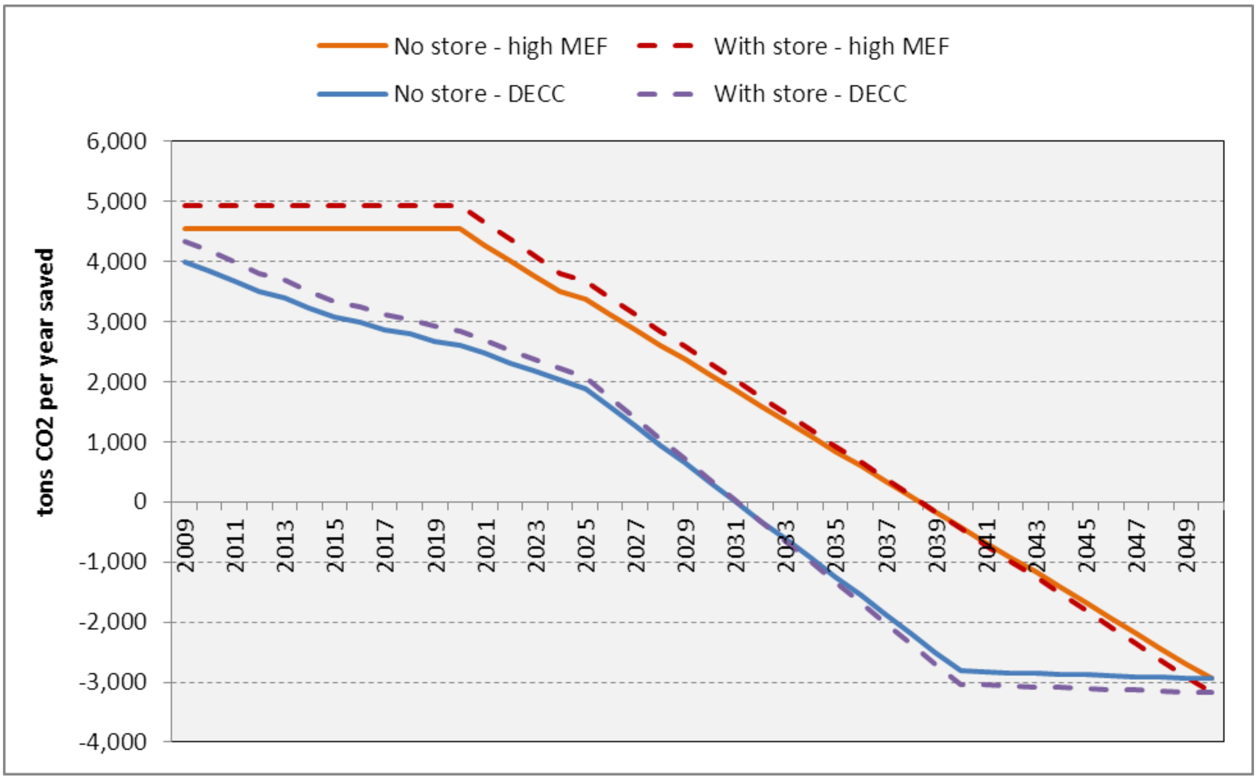


Fig. 5. Carbon emissions saved using MEFs and MEFs for 21,030 MWh/yr heat load.



The difference in annual carbon savings between the two heat loads reflects the greater utilisation of CHP plant required to fulfil the load and consequent increase in electricity production. Using the lower MEFs, the system saves CO_2 emissions until 2031 whilst using the higher MEFs, there are net savings until 2038.

The effect of store size is depicted in **Fig. 6**. The addition of a thermal store improves carbon savings and these are summarised in **Table 4** below, however, there is a limit to the store size beyond which the benefits are marginal.

Fig. 6. Aggregated carbon savings versus store size for period 2014 to 2035

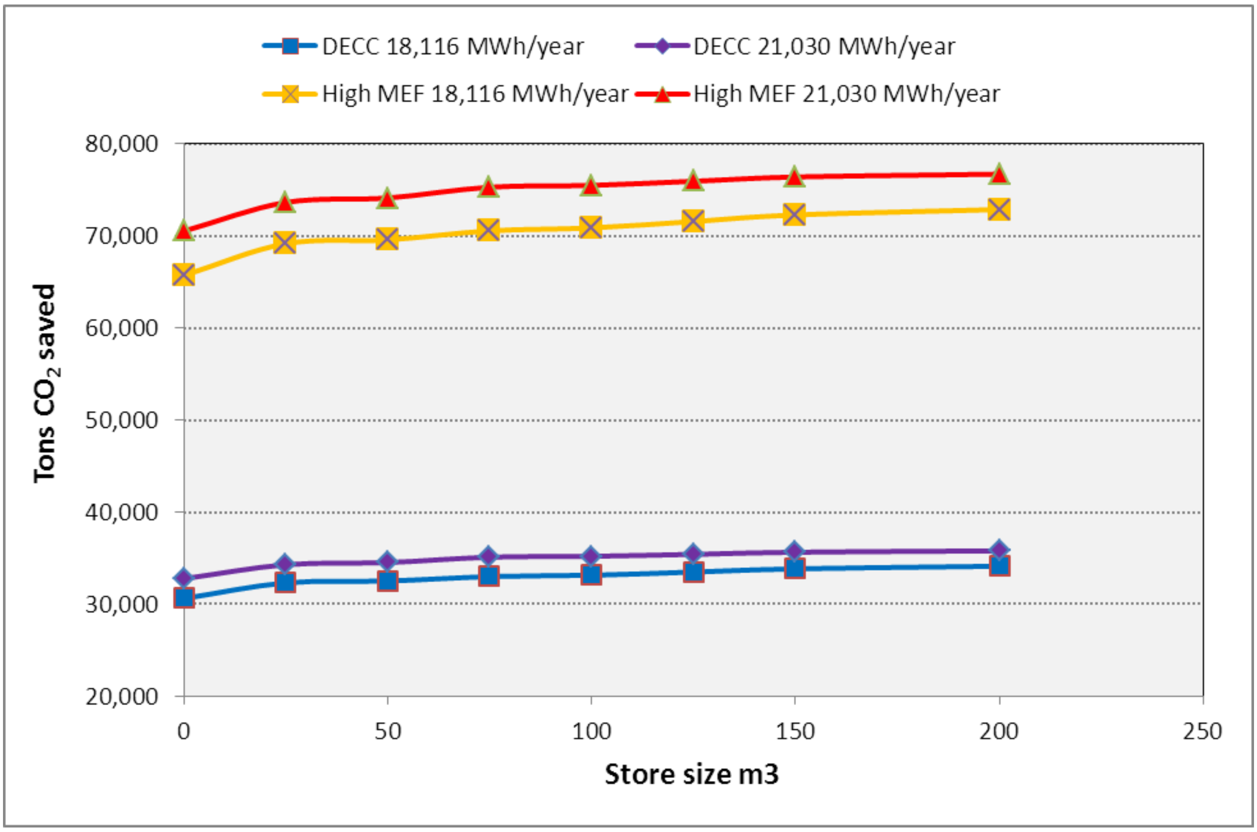


Table 4 –Carbon savings improvements summary over 21 year CHP lifetime

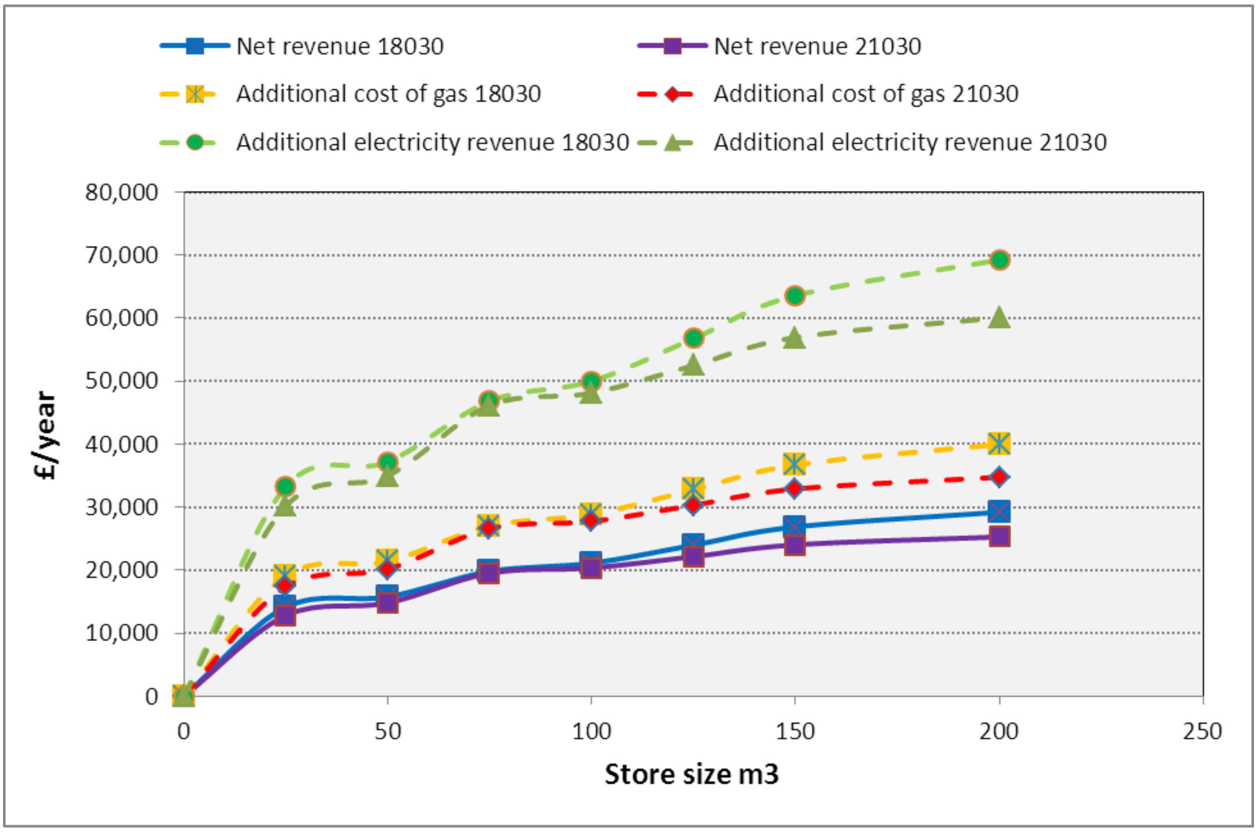
MEF	Heat Load MWh/yr	Carbon savings (tons)		Increase in carbon saved tons	% Increase
		No store	With 150m^3 heat store		
DECC	18,116	30,626	33,727	3,101	10.13
Hawkes	18,116	65,722	72,137	6,451	9.82
DECC	21,030	32,776	35,534	2,758	8.42
Hawkes	21,030	70,535	76,293	5,758	8.16

6.2 Financial Costs

6.2.1 Electricity production and gas consumption

The use of a thermal store permits the CHP units to be run for a greater number of hours during the course of the year for the same overall heat output due to less recourse to peak load boilers. The result is a favourable increase in net revenue due to the greater quantity of electricity sold to the purchaser taking into account higher fuel consumption, as depicted in **Fig. 7** below, but without estimated additional maintenance costs,. Whilst the increase gas costs represent the greater part of the operational cost increase, the difference in the price of electricity and cost of gas, known as the “the spark-gap” is crucial in maintaining a positive revenue benefit for the system operator.

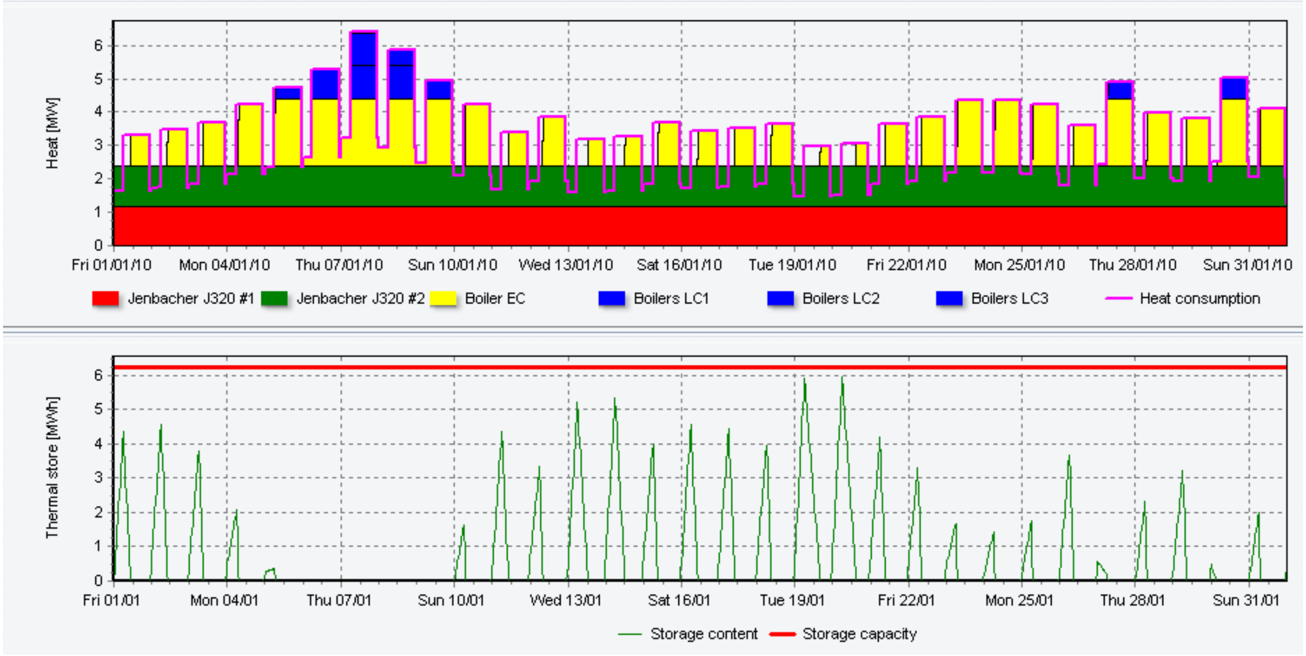
Fig. 7 Income from greater electricity production versus store size for both heat loads.



6.3 The importance of correctly sized CHP plant

Provided the CHP plant is correctly sized for the system heat load, the increase in additional income from electricity production should outweigh the cost of additional fuel consumed. However, if the CHP plant is undersized then the CHP plant will already be operating at maximum capacity in terms of the number of running hours to meet the heat load during the colder period of the year. As a consequence, for some part of the colder period of the year when electricity prices tend to be higher, the CHP plant will be unable to generate sufficient surplus heat to fill the store and therefore the store will play no part in meeting peak heat demand. In other words, the CHP capacity of the system may be too low to realise the full benefit of the thermal store, thus bringing into question the financial case for the store. This effect is demonstrated by comparing outputs from energyPRO for the two test heats loads of 18,116MWh/pa in **Fig. 8.** and 21,030MWh/yr in **Fig. 9.** overleaf.

Fig. 8. CHP and store performance for January for 18,116 MWh/year heat load



The upper chart shows the system heat demand as the line in magenta with heat contributions from the CHP plant and boilers. Where there is a gap between the line and the heat contributors – as can be seen on Friday morning on 01/01/10 – the heat deficit is being made up by the thermal store, as depicted in the lower chart.

Although the CHP plant is working flat out, on most days the thermal store is being charged during the night when heat demand is low. The store is therefore able to provide additional heat during the mornings when heat demand is high, thus mitigating the need for peak load boiler input. Despite this, peak load boilers are called upon on all days although the second tier of boilers (LC1, 2 and 3) are only called upon on 7 days.

In **Fig. 9** below, the CHP plant is working continuously as in **Fig. 8** above, but the thermal store is only partially charged during the night when heat demand is lower. The store is therefore underperforming and consequently there is more recourse to peak load boilers the second tier of which are called upon on for 14 days during the month i.e. twice as often as in the case with the 18,116 MWh/pa heat load.

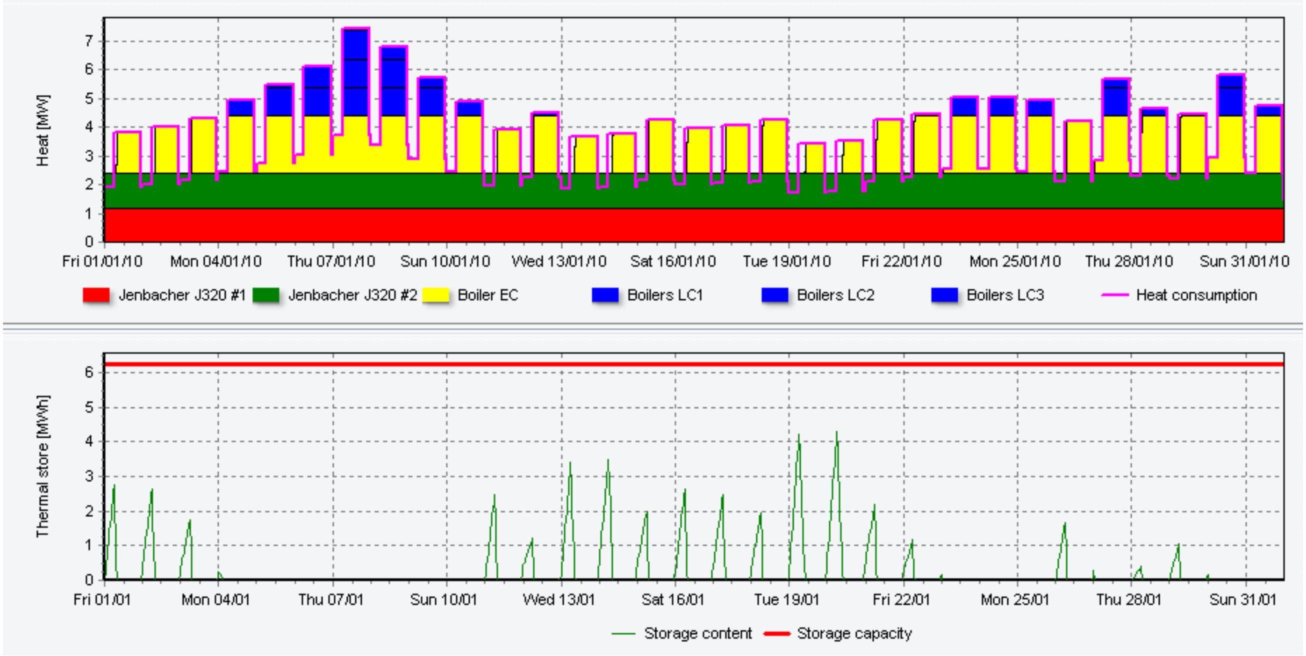


Fig. 9. CHP and store performance for January for 21,030 MWh/year heat load

6.4 Seasonal variations

The pattern of store utilisation varies according to ambient temperature and wind conditions as described below for three periods during the year, namely, winter, mid-season i.e. spring or autumn, and summer. In all three periods, system behaviour is depicted for the reference case without storage and with a 150m^3 store for a ten day period.

6.4.1 Winter

Figs. 10 a) and b) overleaf depict system behaviour at the beginning of January. Focussing on the first three days, in the case without a store the second CHP engine is switched on three times to meet the daytime heat demand with the energy centre (EC) boiler supplying heat during the night. The lower end of the performance range of the CHP plant is limited to 50% of full power and therefore if there is insufficient heat demand then the plant has to be switched off. In the case with thermal storage, the plant may continue to run with surplus heat being used to recharge the store.

For most of the remaining seven days, all of the heat from the CHP plant is required to satisfy system heat demand and therefore the store cannot be recharged and is not utilised.

Fig. 10 a) CHP without store performance for a ten day period in winter

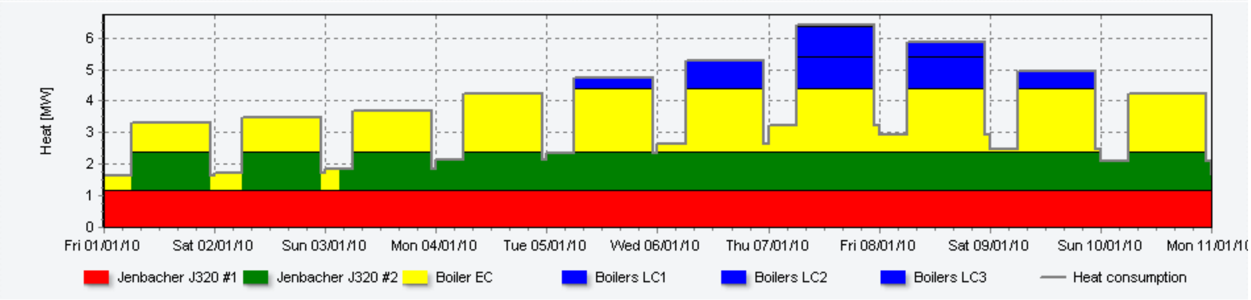
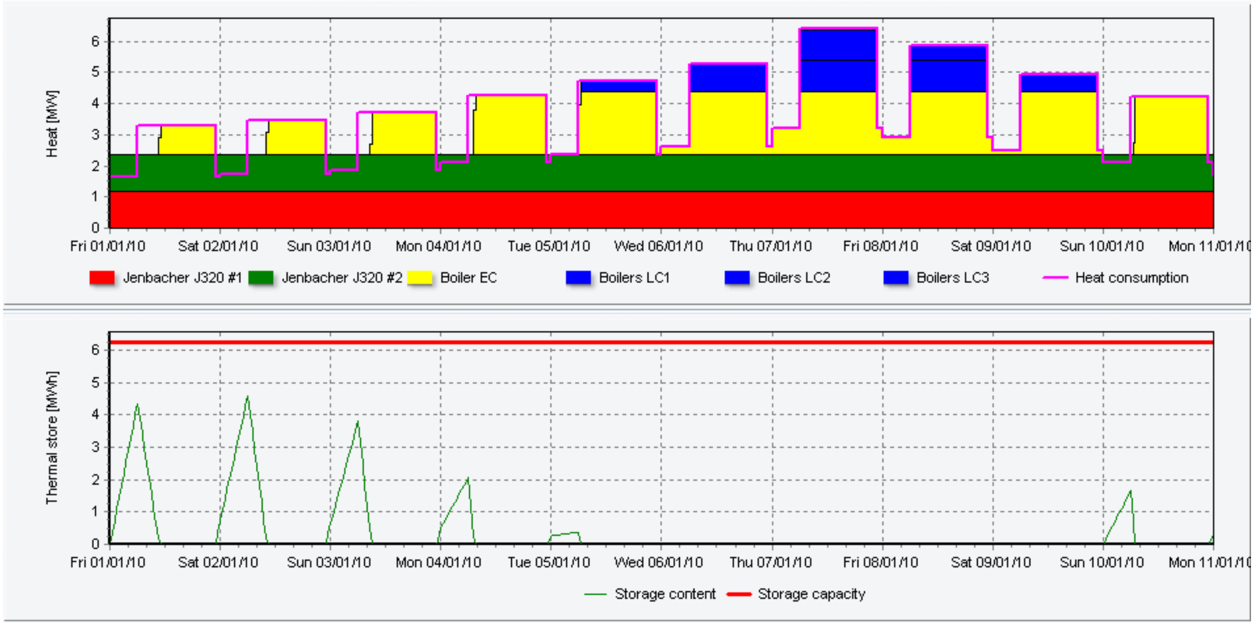


Fig. 10 b) CHP and store performance for a ten day period in winter



6.4.2 Mid-season

Figs. 11 a) and b) depict system behaviour starting from early April. During this period, in the case without thermal storage, the second CHP engine is switched on eight times to meet the daytime heat demand with the EC boiler satisfying any remaining heat. In the case with thermal storage, the CHP plant is able to meet the system heat demand as well as generating surplus heat for recharging the store during the night. For this ten day period, the second CHP plant is only switched on four times and the store utilisation is high, hence it is able to partially displace the EC boiler especially in the morning high demand period.

Fig. 11 a) CHP without store performance for a ten day period in spring

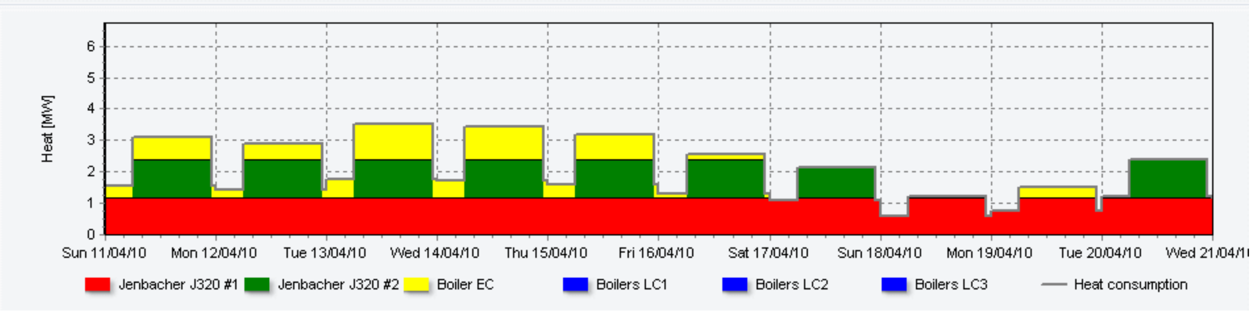
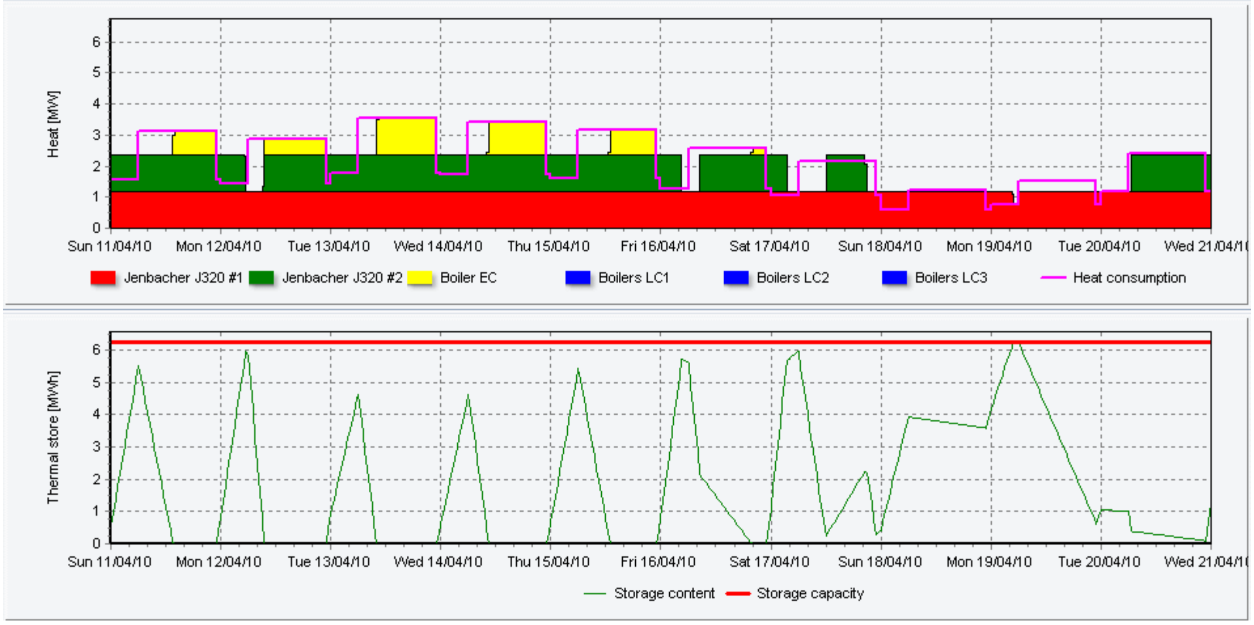


Fig. 11 b) CHP and store performance for a ten day period in spring



6.4.3 Summer

Figs. 12 a) and b) depict system behaviour starting from the end of May. During this period the second CHP engine is switched on only twice to meet the daytime heat demand at the beginning of the period. In the case without thermal storage, the EC boiler is used on eight occasions to meet the night-time heat demand which falls below the minimum power rating of the CHP plant.

In the case with thermal storage, the boilers are not used at all since the CHP plant is able to recharge the thermal store after 11pm which is then used to meet the morning high demand period in the first two days and subsequently the night-time heat demand when the CHP is switched off.

Fig. 12 a) CHP without store performance for a ten day period in summer

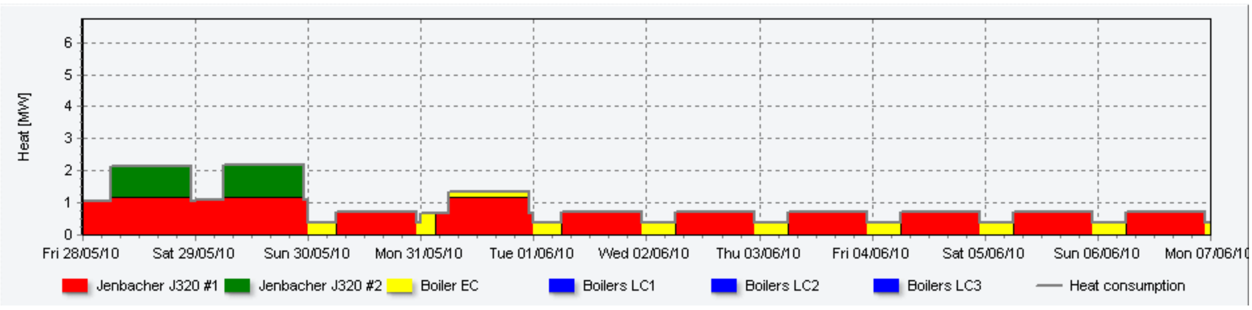
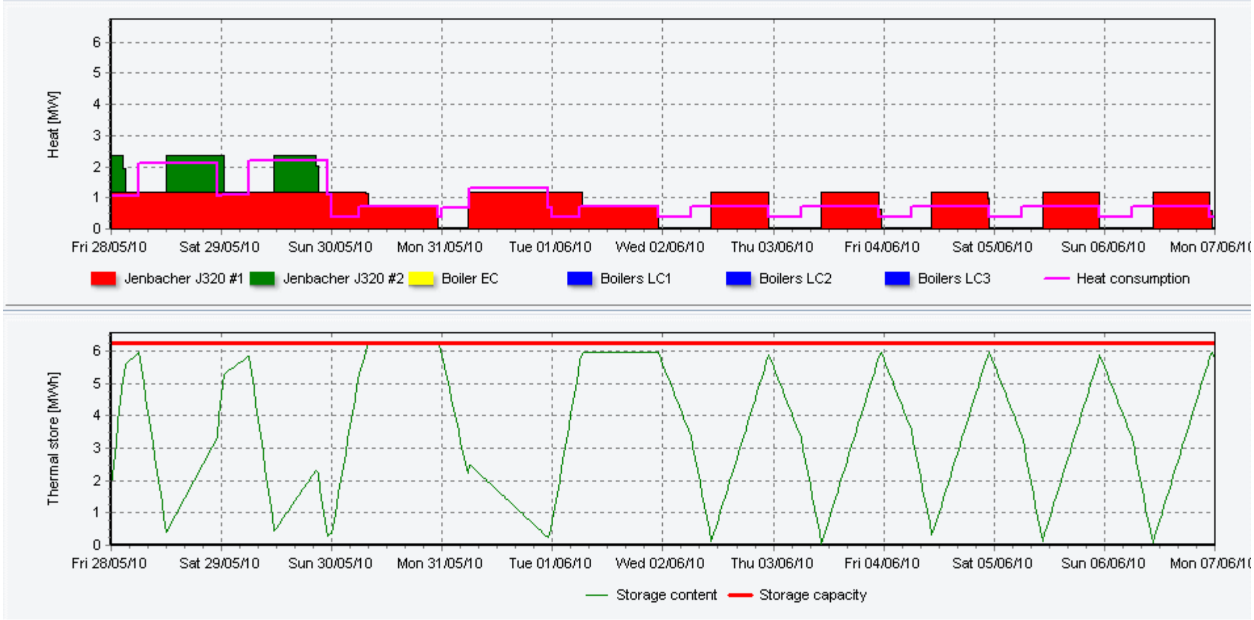


Fig. 12 b) CHP and store performance for a ten day period in summer



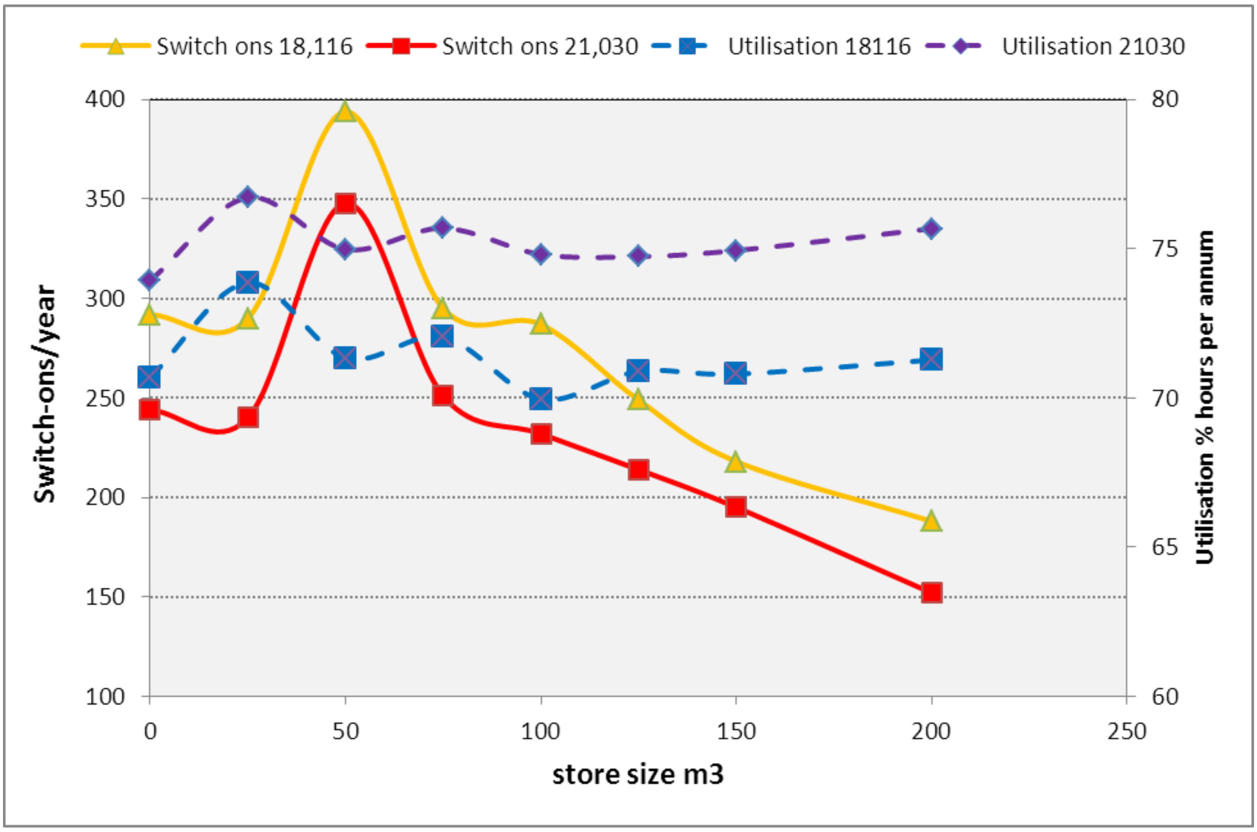
6.5 Maintenance considerations

An important metric when considering the advantages of thermal storage is the number of CHP engine switch-ons and running hours per annum. Maintenance contracts will often require that there should be no more than two switch-ons per day or 60 per month to mitigate the negative impact of start/stop cycles on plant service life. Contracts will also stipulate a maintenance charge relating to the number of the hours of CHP operation which, in some cases, is expressed as a set number of pence per kilowatt hour of electricity produced.

Fig. 10 below depicts the number of switch-ons of CHP plant together with the plant utilisation in the course of a year versus thermal store size for the two heat loads for the test case. Utilisation is measured in terms of the percentage of all hours in the year for which the CHP plant is running.

The results indicate that provided the thermal store is of sufficient size, then, compared with the reference case with no storage, there will be a decrease in the number of switch-ons of CHP plant in the course of a year. However, this needs to be offset against greater plant utilisation in terms of a moderate increase in numbers of hours of CHP plant operation. When considering the increase in utilisation it should be noted that gas reciprocating engines can be operated at partial load down to 50% of full power, consequently the rise in utilisation against store size is less marked compared to the rise in electricity output as depicted in **Fig. 7.** In other words, when the heat load is low the operator has the option of running the CHP plant at full load whilst charging up the thermal store in contrast to the reference case without a thermal store, when the operator would either run the CHP plant at partial load or switch it off and rely on the heat-only boilers.

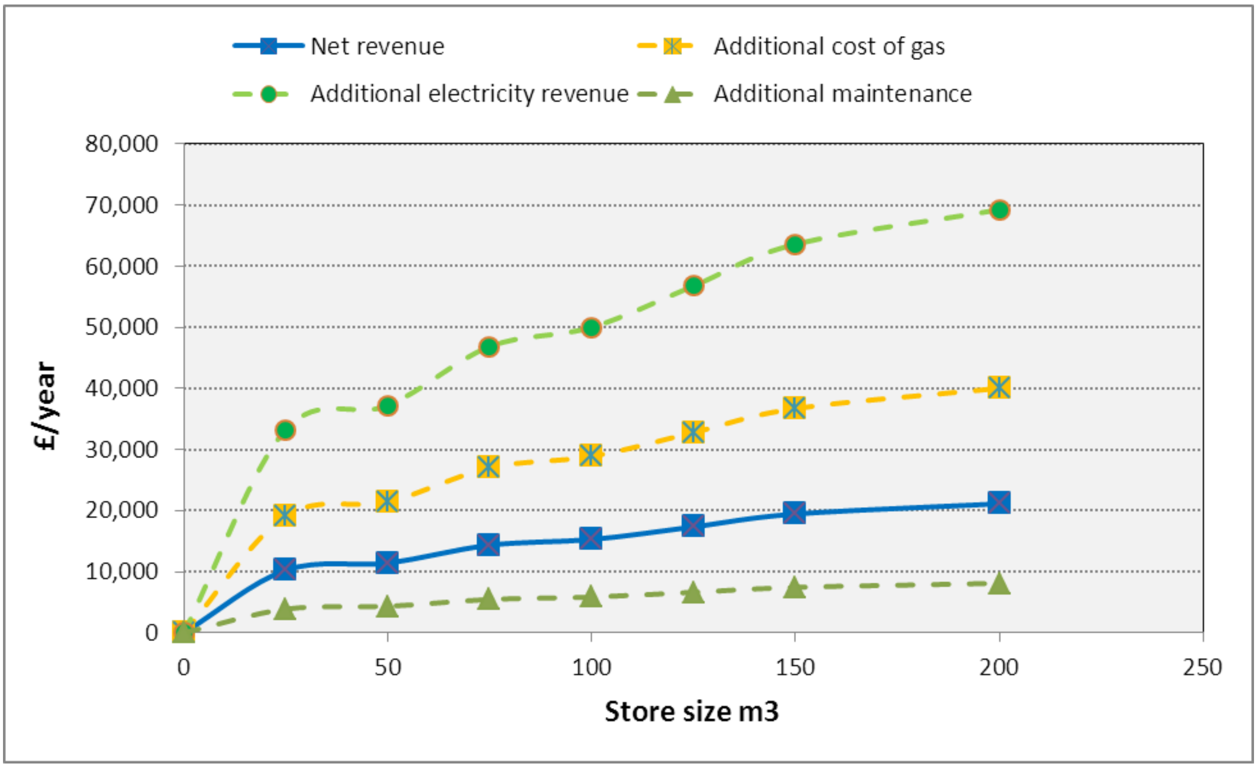
Fig. 10. Numbers of CHP switch-ons and utilisation†



†Utilisation is measured in terms of the percentage of annual hours for which the CHP plant is operating.

If the maintenance contract stipulates a charge which relates to CHP electricity output, then maintenance costs could be expected to rise by approximately 10% compared with the reference case without storage due to the greater CHP plant electricity output. This would decrease net revenue from the additional electricity minus the cost of gas by about 28% as depicted in **Fig. 11** for the test case with the 18,116MWh/per annum heat load and a maintenance charge of 6.5p per kWh of electricity generated. However, if maintenance charges relate to plant running time, then the negative impact on net revenue is almost insignificant.

Fig. 11. Income from additional electricity production taking into account maintenance



7. Discussion

The results depicted in **Figs. 4-6** and **Table 4** demonstrate that the grid emissions factors are crucial to determining the annual amount of carbon saved. In the case with an 18,116MWh per annum heat load and a 150m^3 heat store, there is an additional carbon saving of 3,101 tons when using DECC MEFs which represents a 10% improvement over the reference case and equates to an average saving of 148 tons of CO_2 emissions per annum. Thus the 115 tons of carbon embodied in a 150m^3 store will be paid back within approximately nine months of operation. If the higher MEFs based on the work by Hawkes are used then average savings are more than doubled to 307 tons per annum thus shortening the pay-back period to approximately five months.

The results depicted in **Figs. 7** and **11** confirm the economic viability of adding thermal storage as demonstrated in the Fragaki study [??] on the basis of current natural gas prices and additional revenues from electricity sales.

For a system where the CHP utilisation is already high, in other words, where CHP heat output fails to meet system heat demand for significant parts of the year, it may not be possible to increase CHP utilisation to provide sufficient additional electricity to justify the financial and environmental case for thermal storage. For the test case with a heat load of 21,030 MWh/yr this is effect is apparent in winter compared with the case with an 18,116MWh/yr heat load as depicted in **Figs.9** and **8**. However, despite this limitation, worthwhile benefits in terms of additional revenue and CO_2 savings are achieved for the higher heat load case over the duration of the year.

Figs. 10, 11 and **12** compare the test case with an 18,116MWh/yr heat load with thermal storage against the reference without storage for winter, mid-season and summer. In winter time, the store permits a longer period of operation of the CHP plant between switch-offs with some reduction in the use of boilers although on the colder days the CHP plant is fully deployed meeting the heat demand and therefore the store plays no part. In mid-season the thermal store reduces boiler usage, the number of switch-ons and the need to run CHP plant at less efficient partial loads. In summer, the store enables the boilers to be switched off for long periods and partial load operation of CHP plant to be reduced.

The effect of thermal store size on CHP maintenance priorities is depicted in **Fig. 10**. If the store is too small then, the number of switch-ons increases significantly but for a correctly sized store the numbers of the switch-ons are reduced by 25% in the case of the 18,116MWh/yr heat load and a 150m^3 store and 35% with a 200m^3 store. Plant utilisation is also improved although this is reflected more in terms of less partial load running rather than increased running hours, specifically, total CHP running hours increase by just 0.14% but electricity production is increased by 9.5% with the 150m^3 store and in the case with the 200m^3 store running hours increase by 0.52% and electricity production by 10.4%. There is therefore a clear incentive for the operator to negotiate a maintenance contract for their CHP plant which is based on running hours rather than electricity output as this will negatively impact the net revenue again from the increased electricity sales as depicted in **Fig. 11**.

8. Conclusions

Previous research has established a compelling case for the improved viability of CHP-DH systems with thermal storage compared to the reference case of no storage. This study builds on this by demonstrating significant carbon emissions savings achievable through the addition of thermal storage in the test case of a CHP-DH system which uses gas reciprocating engines typical of many CHP-DH systems in the UK. The use of the energyPRO modelling program has been central to the analysis.

The useable heat and electricity produced by CHP plant delivered via a DH network displaces heat produced by building scale boilers and electricity with a higher carbon intensity drawn down from the grid. The addition of thermal storage to the CHP-DH system test case enables a greater annual quantity of electricity to be produced compared with the reference case with no storage. There is therefore an increase in carbon emissions from the CHP-DH system itself but this is offset from grid supplied electricity with a higher emissions factor which otherwise would be drawn down if the additional electricity was not produced.

The analysis shows that the embedded carbon of the store, supply pipes and foundations are rapidly paid back by the additional carbon savings resulting from the more efficient operation of the CHP-DH system and consequent displacement of grid electricity.

There is a risk that the carbon savings which have been identified may reduce in the longer term if the carbon intensity of plant on the National Grid reduces at greater rate than is currently anticipated.

There will be some additional maintenance related carbon costs for consumables e.g. lubricating oil, filters etc. which could be taken into account due to the greater plant utilisation in the case with thermal storage but these should be minor. CHP plant life may also be improved through the reduction in the number of annual plant switch-ons n the case of thermal storage due to greater utilisation of the plant but this may be offset by greater utilisation.

In some cases peak load boilers could be decommissioned due to their lower utilisation which might also result in further emissions reductions in cases where these boilers are fuelled by oil or coal rather than by natural gas.

Although the benefits of thermal storage can be clearly demonstrated in relation to carbon savings and additional income from increased electricity sales, the barriers to retro-fit are significant, for example, the total cost a retro-fit could approach £250,000 in the test case and the installation of additional control instrumentation would require changes in operational practice. The financial case carries risk due to the uncertainty attached to future gas prices which could narrow the "spark-gap" and is less attractive where CHP maintenance costs are related to electricity production.

Some form of Government support perhaps in the form of VAT relief or access to loans at preferential rates would make the case for retro-fit more attractive for Energy Supply Companies (ESCos) **[iv]**.

More work needs to be done to:

a) Extend the analysis to CHP-DH schemes which use other types of generation plant such as steam turbines fuel by energy from waste plants.

b) Improve estimations of embodied carbon in the additional instrumentation required in the case of retro-fit.

[iv] An Energy Services Company (ESCo) operates and manages different energy supply options and is responsible for procuring the equipment necessary to supply the required energy and the costs of managing and maintaining it. For more detail see DECC, Community Energy Governance structures: http://ceo.decc.gov.uk/en/ceol/cms/process/stage_3/plan/governance_str/governance_str.aspx

Also, guidance is available from the London Energy Partnership's 'Making ESCOs Work', 2007-02: http://www.lep.org.uk/uploads/lep_making_escos_work.pdf

Appendix 1. Embodied carbon

			Kings Cross	Commonwealth Village	Bunhill
Thermal Store dimensions	Volume of water	m^3	74	73	115
Carbon Steel	Estimated volume	m^3	78.25	62.18	130.29
	Diameter	m	2.50	2.50	3.60
	Radius	m	1.25	1.25	1.80
	Weight	kg	12,000	17,000	19,000
	Volume of steel	m^3	1.529	2.166	2.420
	Embodied Carbon - vessel	**$kgCO_2$**	**49,392**	**69,972**	**78,204**
Electric Welding	Length	m	7.9	7.9	11.3
	Embodied Carbon - welding	**$kgCO_2$**	**2**	**2**	**3**
Cylinder with hemispherical ends	Height of Cylindrical section	m	14.275	11.000	10.400
	Surface area	m^2	141.6	115.8	178.7
	Insulation Thickness	m	0.1	0.300	0.125
	Volume of insulation	m^3	14.16	34.75	22.34
	Embodied Carbon - insulation	**$kgCO_2$**	**1,274**	**3,128**	**2,010**
	Wood cladding thickness	m			0.044
	Volume of wood cladding	m^3	0.00	0.00	7.86
	Embodied Carbon - wood cladding	**$kgCO_2$**			**3.62**
	Aluminium stucco cladding thickness	m	0.010	0.010	0.010
	Volume of aluminium cladding	m^3	1.42	1.16	1.79
	Embodied Carbon - Al cladding	**$kgCO_2$**	**0.65**	**0.53**	**0.82**
Pipes	Length	m	10	10	10
DN ("Diametre Nominal")	Diameter	m	0.050	0.050	0.050
Carbon steel	Thickness	m	0.022	0.022	0.022
	Volume of steel	m^3	0.035	0.035	0.035

	Embodied Carbon	**kgCO$_2$**	**1,117**	**1,117**	**1,117**
Valves	Butterfly valves	kg	94.20	94.20	94.20
Carbon steel	Relief valve	kg	0.90	0.90	0.90
	Ball valve	kg	0.45	0.45	0.45
	Volume of valves	m^3	0.0122	0.0122	0.0122
	Embodied Carbon	**kgCO$_2$**	**4.65**	**4.65**	**4.65**
Strutts	Length	m	2	2	2
DN ("Diametre Nominal")	Diameter	m	0.050	0.050	0.050
Carbon steel	Thickness	m	0.022	0.022	0.022
	Volume of steel	m^3	0.007	0.007	0.007
	Embodied Carbon	**kgCO$_2$**	**223**	**223**	**223**
Concrete Base	Length	m	5.83	6.60	6.05
	Surface Area	m^2	33.99	43.56	36.60
	Depth	m	0.30	0.40	0.50
	Volume of concrete	m^3	10.20	17.42	18.30
	Embodied Carbon	**kgCO$_2$**	**3,895**	**6,656**	**6,991**
Instrumentation	**Embodied Carbon**	**kgCO$_2$**	**4.65**	**4.65**	**4.65**
	Total Embodied Carbon	**kgCO$_2$**	**55,689**	**80,884**	**88,561**

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