Design Intent compared with Performance in Practice: Residential Heat Networks with Combined Heat and Power

Christopher Nicholas Marien

Darwin College

Department of Engineering

University of Cambridge

This dissertation is submitted for Doctor of Philosophy

September 2019

Declaration

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text.

It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. It does not exceed the prescribed word limit for the relevant Degree Committee.

Christopher Nicholas Marien
cnm29

Acknowledgements

This research would not have been possible without the support of my industry sponsor and employer calfordseaden LLP.

I would like to express my gratitude to my supervisor Dr Sebastian Macmillan. Our discussions and his guidance have been invaluable to this research and my progression as a researcher.

A further special thanks to my external industry advisor Dr Terry Keech for his continued professional and academic support.

Christopher Nicholas Marien

Design Intent compared with Performance in Practice: Residential Heat Networks with Combined Heat and Power

Abstract

The GLA's London Plan includes planning policies that require developers to adopt a range of energy efficient measures and low/zero carbon technologies to reduce CO_2 emissions below the Building Regulations baseline. Such polices have consequently formed a new aspect of the planning appraisal process, where the assessment of energy, CO_2 and technology is now a material consideration of planning approval. Developers must submit an energy strategy to demonstrate how their design proposals achieve the policy targets. The GLA uses these documents as evidence to evaluate the outcomes of the existing policy and direct future policy decisions. The GLA's findings suggest that their policies have been successful in reducing CO_2 emissions. The vast majority of reductions are attributed to heat networks with CHP. However, there is little evidence of the actual performance of these technologies in practice, including the scale of CO_2 emissions reductions delivered.

This research adopted a mixed method approach to evaluate if the local energy policies which promote the adoption and implementation of heat networks and CHP are leading to the anticipated reductions in CO_2 emissions. This research found that the prescriptive approach to the London Plan policy discourages context specific assessment and can lead to a practice of compliance-over-performance when deciding on the most appropriate technology to adopt. The prescribed assessment methodology was also found to be inadequate to appropriately assess the deliverable performance and would therefore, result in an energy performance gap. The research also found that design assessment measures are available to provide a more reasonable assessment of deliverable performance reducing the gap, but are not used in practice. Furthermore, those responsible for implementing the policy do not expect that the assessed performance of heat networks and CHP or the scale of CO_2 emissions saved will be achieved in practice, contrary to the GLA findings.

Contents

List of Tables

List of Figures

List of Abbreviations

ade	Association of Decentralised Energy
AE	Auxiliary Energy
AMR	Annual Monitoring Report
BEMS	Building Energy Management System
BRE	Building Research Establishment
BREDEM	Building Research Establishment Domestic Energy Model
CfSH	Code for Sustainable Homes
CHP	Combined Heat and Power
CHPQA	CHP Quality Assurance Programme
CIBSE	Chartered Institute of Building Services Engineers
CO_2	Carbon Dioxide Emissions
CS	Case Study
CV	Calorific Value
ADL1	Approved Document Building Regulations Part L1
DE	Decentralised Energy
DHGE	District Heating Global Efficiency (equation 7)
DHL	Distribution Heat Loss
DHW	Domestic Hot Water
DLF	Distribution Loss Factor (equation 3)
DUKES	Digest of UK Energy Statistics
E_{aux}	Auxiliary Energy
ECHP	CHP Electrical Generation
E_{del}	Thermal Energy Delivered
E_{gen}	Thermal Energy Generated
EiP	Evaluation in Public
E_j	Primary Energy Consumption
E_{loss}	Distribution Heat Loss
EPG	Energy Performance Gap
EPI	Energy Performance Indicators
ES	Energy Strategy
FALP	Further Alterations to the London Plan
GLA	Greater London Authority
HD	Heat Density (equation 1)
HIU	Heat Interface Unit
HM	Heat Meter
HN	Heat Network
HN-CHP	Heat Network with CHP
LA	Local Authority
LHD	Linear Heat Density (equation 2)
LPA	Local Planning Authority
LZC	Low or Zero Carbon

PEE	Primary Energy Efficiency (equation 6)
PEF	Primary Energy Factor (equation 4)
POE	Post-Occupancy Evaluation
RE	Renewable Energy
RiL	Relative Importance of Losses (equation 5)
SBEM	Simplified Building Energy Model
SAP	Standard Assessment Procedure
SH	Space Heating
SPG	Spatial Planning Guidance
ST	Solar Thermal
TLP	The London Plan

CHAPTER 1: RESEARCH INTRODUCTION

This chapter introduces the thesis through a description of the focus and the rationale behind the research. The author's background in professional practice is explained in addition to how this has informed the research subject. This chapter will outline the research aim and objectives. It concludes with a description of how the remainder of the thesis is structured.

1.1 Motivation

As a practising Chartered Building Services Engineer, the author of this research and PhD candidate has worked for over ten years in the Mechanical, Electrical, and Sustainability team at the multi-disciplinary design consultancy calfordseaden LLP.

Working with some of the largest housing associations and house builders in the country, the design and construction of low carbon homes is a major business area for calfordseaden. The extent of the author's professional practice in the field of building services design and construction includes concept design, planning permission, contract procurement, detailed design, construction and post-occupation evaluation. As an engineer working within a collaborative engineering and sustainable design team that includes Code for Sustainable Homes (CfSH), Building Regulation Standard Assessment Procedure (SAP), Energy Performance Certification and BREEAM assessors, the author has benefited from a holistic approach to low energy building services design, assessment and monitoring of low carbon buildings. This has given the author a wealth of knowledge and in-depth understanding of fundamental principles that underpin the industry's approach to sustainable design and the assessment methodologies.

The initial idea for the research developed from the growing professional practice of post-occupancy evaluations of new buildings that are accredited as 'low carbon'. Furthermore, the expanding professional discussion regarding the energy performance gap (EPG) in industry journals and conference papers. The author identified a point within the project process when key decisions are made regarding the adoption of energy efficiency measures and technologies. This was identified as the planning stage when the projects energy strategy (ES) is designed, including the commitments of CO_2 emissions (CO_2) reductions through the installation of low or zero carbon (LZC) technologies. To date this point of the project process has received little apparent attention from academic and industry study, but in the author's opinion an influential stage of a project. As a Chartered Engineer, the author considered it his responsibility to investigate and share the findings within his professional community of practice.

1.2 Context and Focus

Owing to the threat of climate change, depletion of national energy resources and rising costs of imported fossil fuels, the UK Government has implemented national strategies across a spectrum of sectors to safeguard the UK's future energy needs and combat climate change. Many sector specific policy and guidance documents have been published outlining how the UK will achieve its ambitious CO_2 reduction targets towards 2050. The reduction of CO_2 associated with buildings, approximately a third of all UK CO_2, is a sector with vast opportunity for reductions (DECC, 2011).

To reduce CO_2 in the built environment, top-down and bottom-up policies have been implemented to deliver reductions from new buildings. Top-down drivers from national level include: iterative enhancements to existing legislation (Building Regulations Part L), financial grants (Feed-in-Tariffs and Renewable Heat Incentive), sustainable design standards (CfSH and BREEAM) and strategic publications directing local level policy (dti, 2003 & 2007; DECC, 2011).

This research focuses on the bottom-up actions taken at the regional and local level, specifically in urban planning, where local planning policy imposes strict CO_2 reduction targets and promotes the adoption of energy efficiency measures and LZC technologies. Following the Planning and Compulsory Planning Act (2004), regional and local planning authorities (LPA) have been directly responsible for setting planning policy through regional strategies and local plans. This includes setting policy to combat climate change through reducing energy consumption and the resulting CO_2 in new buildings. Integrating CO_2 reductions targets within the remit of LPA was intended to ensure that as a prerequisite of planning permission new building developments consider energy efficient design. These measures are aimed to reduce the energy use and the subsequent CO_2 beyond the current Building Regulations compliance baseline. Furthermore, LPA's are expected to implement other strategic plans such as the promotion of decentralised energy (DE) through connection to existing, or establishing new, heat networks (see section 3.1 for detailed description of a heat network), the integration of Combined Heat and Power (CHP), and the installation of onsite renewable energy (RE) technologies. A HN is the transfer of heat from a centralised heat source (e.g. gas boilers) to a remote end consumer (e.g. dwelling). A CHP is the cogeneration of heat and electrical power in a single process (refer to section 3.1 and 3.3 for detailed descriptions of HNs and CHP).

This research focuses on the Greater London and the City of London (hereafter referred to as London) as its spatial boundary. The Greater London Authority (GLA) has implemented its strategic plan ‘the London Plan’, which includes a target of 60% CO_2 reduction by 2025 over levels experienced in 1990 (GLA, 2008). The London Plan (TLP) aims to achieve this through policies that ensure all new major developments incorporate measures to improve energy efficiency, maintain or create heat networks (HN), integrate CHP, and consider the installation of onsite RE technologies. London is an area of substantial growth in new building developments (the London Mayor Sadiq Khan, has promised to build 50,000 new homes a year to meet current demand), therefore there will continue to be significant delivery of ‘low carbon homes’. London is also the second highest region of domestic energy consumption in the UK (Mayor of London, 2017). Therefore, this region is of strategic importance in meeting the UK’s CO_2 targets. For these reasons London is the ideal political, spatial and social-technical landscape to conduct this research.

DE in the form of HN with CHP (HN-CHP), is of strategic importance within the national energy strategy and TLP. These technologies are seen as a way of decarbonising the heating supply in buildings and easing the path for the integration of other LZC technologies. TLP expects 25% of heat and power requirements to be met by using local DE systems by 2025 (GLA, 2016a p.188).

The recent GLA policy monitoring reports have concluded that there is significant planned uptake in HN-CHP. From planning applications referred to the GLA between 2010 and 2015 over 90% of all new dwellings were planned to be connected to HN and 131.4 MW of planned new CHP capacity was proposed. The GLA attributes over 190 $ktCO_2$ as being saved (over a building regulations baseline) per annum from these technologies (GLA, 2011; 2012; 2013; 2014; 2015 and 2016). DE in the form of HN- CHP is championed by the GLA as the major contributor to the reductions “achieved” in CO_2 (GLA, 2016).

The recent abundance of new buildings (domestic and non-domestic) certified as ‘low carbon’ has increased the level of scrutiny on in-use energy performance. The findings of the

PROBE[1] studies demonstrated that energy consumption can be three times higher than designed (Bordass, Cohen & Field, 2004). This phenomenon has become known as the 'energy performance gap' (EPG). Despite the increased interest from industry and academic researchers there are still few studies that evaluate the EPG in residential buildings and fewer still that evaluate the performance HN-CHP.

However, the house building industry is starting to identify the current issues and inefficiencies in modern HN-CHP systems. Several articles have been published in industry journals identifying the potential inefficiencies and high operating costs in modern HN-CHP. For example:

"In certain cases, it may be possible to prove that the inefficiencies result in a 'high carbon' system – the reverse of policy intention." (Blackwell, 2013)

HN-CHP is the technological focus of this research. Given the policy drivers and significant technology uptake. How these technologies are performing in practice is fundamental to evaluating the success of regional planning policy, such as TLP, to reduce CO_2 in buildings, and ultimately national policy.

1.3 Aims and Objectives

The aim of this research project was to evaluate if the local energy policies that promote the adoption and implementation of HN-CHP technologies in small scale residential buildings are leading to the anticipated reductions in CO_2 emissions. This is investigated to expand the academic research in this field and to inform industry and policy makers of the current outcome of policy to deliver real world CO_2 reductions.

To ensure that this strategic aim of the project is met, several objectives have been defined to enable the research to be focused around the key themes established through engaging with the existing academic research and industry studies. These objectives are:

- Understanding current professional practice related to the creation of an energy strategy, including: the methods of feasibility assessment, evaluation of potential energy and CO_2 savings, and the motives that inform the designers decision to adopt a HN-CHP system.

[1] PROBE - Post-occupancy Review Of Buildings and their Engineering

- Understand how planning policy and guidance influences the selection of LZC technologies, including HN-CHP.
- Establish whether an energy performance gap exists between design intent and performance in practice of a HN-CHP, and if so, the scale and causes of the gap.

The research has identified the necessity for, but the current lack of, evidenced based feedback for government policy, low energy building design and technology performance. Another aim of this research to provide a modest contribution of empirical evidence that provides feedback for policy makers, the housing building industry and the academic research field.

To meet the aims and objectives the research has adopted a mixed method approach including document analysis, case study evaluation and an industry survey. The document analysis identifies common themes and assessment methodology applied in professional energy strategy documents submitted in real world planning applications for new residential buildings. The case study evaluates the actual in-use performance of a HN-CHP system within a case study building. Finally, the industry survey identifies from industry professionals their opinions and perspectives regarding the adoption of local planning energy policy; methods for assessing LZC technologies; and the EPG in HN-CHP systems. The findings from the three methods are triangulated to provide conclusion to the research questions.

1.4 Thesis Structure

The thesis is organised into 9 chapters, structured as follows:

Chapter 1: Introduction. Introduces the thesis and details the context, focus and structure of the research.

Chapter 2: The GLA's Climate Change Strategy. The regional planning policy of TLP is reviewed and findings of the GLA policy monitoring studies are examined. The chapter examines the existing filed of research related to the evaluation of the TLP energy policy and evidence based policy.

Chapter 3: The Application of Heat Networks and CHP in Residential Buildings. The energy policy prioritisation of HN and CHP as a technological solution is examined, providing the historical use of these specific technology in the UK and their theoretical contribution to reduction of CO_2 in buildings. The chapter explores the key technical research and industry guidance related to the performance assessment of these technologies.

Chapter 4: The Energy Performance Gap. A definition of the EPG is presented. The chapter examines the key related research of the EPG in residential buildings and explores the existing research related to the performance of HN-CHP systems.

Chapter 5: Research Questions and Research Design. Primary and secondary research questions are proposed. The research methodology is explained indicating the conceptual framework, research approach, data gathering methods and ethical considerations. The chapter gives justification for the use of mixed methods and outlines a strategy of inquiry framework.

Chapter 6: A Content Analysis of Planning Energy Strategy Documents. A systematic analysis of energy strategy documents submitted in real world planning applications. Data is obtained from analysis of the documents to define themes that guide the proceeding research inquiry. The chapter ends with a reflection on the data obtained and its contribution to answering the research questions.

Chapter 7: Post-Occupancy Energy Analysis of a HN-CHP System. Provides a detailed description of the case study, the techniques and methods used to analyse and compare the design intent and the performance in practice. The chapter ends with a reflection on the data obtained and its contribution to answering the research questions.

Chapter 8: A Survey of Energy Consultants. The chapter details the development and structure of a questionnaire, and reviews the data gathered. The purpose of the survey is to increase the data obtained across a wider field of professional practice. The chapter ends with a reflection on the data obtained and its contribution to answering the research questions.

Chapter 9: Summary of Findings, Conclusions and Limitations. This chapter discusses the findings from the evidence obtained through the completion of the research. The evidence is explored for meaning and triangulated to validate the results. Conclusions are drawn from the findings to answer the research question. The chapter completes a critical review of the research including limitations and future research opportunities.

1.5 Chapter Reflectance

This chapter has introduced the thesis, including the author's motivations and the focus of the research to be completed. The aims and objectives to be completed have been defined. Finally, a summary of the thesis is given to describe each chapter and indicate the journey of discovery undertaken through the research.

CHAPTER 2: LONDON'S CLIMATE CHANGE STRATEGY

This chapter describes the key international and national frameworks of legislation that empowers local planning authorities to enact CO_2 reduction measures through local development plans. TLP climate change strategy for new buildings is examined, including its promotion of HN and CHP. The findings of the GLA's monitoring reports are examined. Finally the relevant research related to the evaluation of the TLP, formation of urban planning policy and evidence based policy is examined.

2.1 The UK's Climate Change Strategy for New Building Developments

To halt and reverse the progress of climate change laws exist at the international (UN and EU) and national levels (UK government and devolved administrations). At the local level, strategic plans and industry best practice interpret the laws into compliance guidance. The remainder of this section does not aim to provide an exhaustive review of the many acts, regulations and policy instruments. Instead it provides an overview of the most relevant legislation and guidance to set the political and technological context for the research.

There are several key national publications that transferred the responsibility for reduction of CO_2 in new buildings from central government into the remit of LPA in addition to initiating a technological prioritisation towards HN and CHP.

The UK's Climate Change Programme set out the UK Government's approach to meet the internationally agreed 1997 Kyoto Protocol and the UK's additional domestic target for a 20% reduction in CO_2 below 1990 levels by 2010 (DETR, 2000). It included proposals to amend the energy efficiency targets of the building regulations and for the first time highlighted the role of the planning system in responding to climate change. The UK's climate change strategy and policy guidance has continued to evolve by strengthening local planning role in tackling climate change. The influence these publications have had on planning policy and the promotion of HN and CHP is outlined in table 2.1.

Table 2.1: UK Climate Change Publications Consequence for Climate Change

Climate Change – the UK's Programme (DETR, 2000)	
Consequence for local planning's role in climate change	• Identified for the first time the planning system's role in combating climate change. • Proposed a 'best practice guide' to help the planning system to respond to climate change.
Consequence for HN and CHP role in Climate Change	• Proposed measures to exempt 'Good Quality' CHP from the Climate Change Levy. • Targeted to double UKP CHP capacity by 2010. • Promoted new communal heating.
Energy White Paper – Out Energy Future (dti, 2003)	
Consequence for local planning's role in climate change	• Proposed regional targets for energy efficiency and renewable energy. • Promoted national objective through local and regional decision making. • Promised a 'best practice guide' for LPA to promote renewable energy through the planning system. • Need for a future examination of how to bring energy efficiency and renewable energy within the scope of the planning system.
Consequence for HN and CHP role in Climate Change	• £60m renewable energy scheme to promote the installation of CHP and renewable energy over a three year period. • Targeted 10GWe of 'Good Quality' CHP by 2010. • New power stations applicants need to provide 'significant evidence' that they have considered CHP and HNs. • When guidance is introduced or renewed it should include emphasize of CHP and HNs. • CHP target for Government department buildings and encouragement of other public sector to consider a CHP target. • Support for field trials of micro-CHP. • Promised a CHP strategy to be published. • £50m DEFRA community energy scheme to aid the installation of new HNs.
The Planning Response to Climate Change (ODPM, 2004)	
Consequence for local planning's role in climate change	• Advice on better practice in planning policy to combat climate change. • Argued climate change is a 'material consideration' of a planning application. • Stated an urgent need for regional and local planning policies for climate change adaption and mitigation. • Promoted the use of sustainability appraisals. • Promoted the use of planning instruments to enforce climate change consideration (e.g. conditions, agreements, obligations).
Consequence for HN and CHP role in Climate Change	• Target to double the capacity of CHP by 2010. • Encouraged the development of CHP schemes and HNs in any mixed-use, high density development and in association with energy intensive industrial processing plants. • Developers encouraged to determine the feasibility of CHP in

	certain types of development.
The Planning Policy Statement 22 (ODPM, 2004a)	
Consequence for local planning's role in climate change	• Eight key principles for planning for renewable energy in new developments.
Consequence for HN and CHP role in Climate Change	• CHP to be specifically encouraged through policy in local development documents.
Planning Policy Statement 1 (ODPM, 2005)	
Consequence for local planning's role in climate change	• Policy must reflect the need for developments to minimise the impact on energy resources.
Consequence for HN and CHP role in Climate Change	• Planning policy to promote HN's schemes and use of CHPs.
Energy White Paper – Meeting the Energy Challenge (dti, 2007)	
Consequence for local planning's role in climate change	• Strengthened the pressure on planners to recognise the need for LZC technologies. • Clear steer to planning professionals and LPA not to question the national need for LZC technologies. • The role of local LZC technologies to achieve the national target is a material consideration and should be given significant weight in reaching decisions.
Consequence for HN and CHP role in Climate Change	• Measures to encourage deployment of CHP. • Create a framework that would allow Energy Service Companies (ESCO) to develop.
Building a Greener Future: Policy Statement (DCLG, 2007)	
Consequence for local planning's role in climate change	• LPA required to identify opportunities for LZC technologies. • Work towards zero carbon homes policy by 2016. • Policy should specify a target for LZC technology in new developments. • Introduce Code for Sustainable Homes as a planning requirement.
Consequence for HN and CHP role in Climate Change	• LPA must have a strategy for securing DF and LZC technologies in new developments.
The Planning and Energy Act (Planning and Energy Act, 2008)	
Consequence for local planning's role in climate change	• LPA could through planning policy, require developments to design beyond Building Regulations energy compliance standards and provide a proportion of the site energy demand through LZC technologies.
Consequence for HN and CHP role in Climate Change	None.

The national publications outlined in table 2.1 have shaped how the local planning policy framework has integrated energy efficiency measures, HN-CHP and RE technologies. Climate change was confirmed as a 'material consideration' for planning authorities, that gave local planning offices the authority to deny planning approval based solely on a development's climate change credentials.

2.2 The London Plan – Response to Climate Change

The focus of this review now examines how planning policy related to climate change is applied through '*The London Plan - Spatial Development Strategy for Greater London*'. Strategic planning in London is the shared responsibility of the Mayor of London, 32 London boroughs and the City of London Corporation. The Mayor must produce a spatial development strategy (The London Plan) and the LPA are expected to conform through their local plan. The first London Plan publication (GLA, 2004a), included specific policy relating to climate change mitigation. It was aimed at achieving a 60% CO_2 reduction (from 1990 levels) by 2025 and delivering 'zero carbon homes'[2] from October 2016. Policies to meet these targets have been incrementally adapted through the proceeding alterations of TLP. Any changes must be considered through a formal Examination in Public (EiP).

As part of London's holistic approach to climate change, there is a range of policies covering a variety of related areas, including: air quality, bio-diversity, green roofs, flood risk management, sustainable drainage, waste, and water quality. These policies are not discussed as part of this thesis.

The GLA includes LZC technologies such as electric heat pumps and biomass as renewable energy (RE) (GLA, 2004 p.68). Therefore, all further references to LZC technologies are defined as RE.

2.2.1 The London Plan – 2004

The first London Plan set policies with the objective of reducing CO_2, improving energy efficiency and increasing the proportion of energy generated from renewable sources (policy 4A.7 and 4A.9). Increasing onsite RE was one of the objectives of the Mayor's energy

[2] Zero Carbon Homes – all onsite regulated energy use (as outlined in Building Regulations Part L1A) are to be mitigated through various measures. Energy and CO_2 emissions resulting from cooking and plug-in appliances are not included as part of the policy (ZCH, 2019).

strategy '*Green light to clean power*' (GLA, 2004). The strategy introduced an 'energy hierarchy' to guide the decisions when selecting appropriate energy efficiency, HN-CHP and RE measures. The hierarchy was considered by the GLA to be appropriate guidance for a range of stakeholders, architects, planners, developers and individual home owners.

The Energy Hierarchy (GLA, 2004):

1. Use Less Energy (Be Lean):

- *Reduce consumption through behavioural change*
- *Improve building insulation*
- *Incorporate passive heating and cooling*
- *Install energy efficient lighting and appliances*

2. Use Renewable Energy (Be Green):

- *On-site: install renewable energy technologies such as wind, solar water heating, solar photovoltaic and biomass.*
- *Off-site: import renewable energy generated elsewhere.*

3. Supply Energy Efficiently (Be Clean):

- *Use combined heat and power, and heat networks (community heating, district heating).*
- *Cut transmission losses through local generation.*

Although positioned last in the energy hierarchy, the Mayor's energy strategy emphasised the importance of HNs and CHP. It was a GLA target to double the capacity of CHP between 2000 and 2010. All planning applications referring to the Mayor were required to include a HN and CHP "where viable" (GLA, 2004 P.15) and all LPA's were expected to apply this same requirement.

In addition to the energy hierarchy, the selection of heating and cooling technologies was given an 'order of preference', which ranked technologies from most to least preferred (GLA, 2004a):

1. *Passive design (e.g. Passivhaus)*
2. *Solar water heating*
3. *Combined heat and power*
4. *Community heating and cooling*
5. *Heat pumps*
6. *Gas condensing boilers*
7. *Gas central heating*

To demonstrate that the Mayor's strategies are being adopted, developers are required to submit an 'energy strategy' (ES) (also known as an 'energy assessment' or 'energy statement'). An ES demonstrates how the energy hierarchy has been applied within the design of the proposed development to achieve the target levels of energy demand and CO_2 reduction (GLA, 2004a, Policy 4A.8).

In 2006, the first proposed alterations were published as '*Draft Further Alterations to the London Plan'*; formally adopted in 2008. The alterations included a prominent shift to the prioritisation of DE (HN-CHP). A minimum percentage reduction target for onsite renewable energy was also considered following the success of a policy introduced by Merton Council. The policy required that all major housing and commercial developments must have a provision to generate at least 10% of projected CO_2 emissions from onsite renewable energy technologies. The policy was widely adopted by other local planning authorities and became known as the 'Merton Rule' (Rydin, 2010 p.246).

2.2.2 The London Plan – 2008

The 2008 London Plan introduced policy that required all developments to prioritise the connection to or establishment of DE networks (GLA, 2008; Policy 4A.5 & 4A.6). The prioritisation of DE (in the form of HN-CHP) was driven by the national guidance to promote DE (dti, 2007) as well as the findings of the GLA's commissioned research. The GLA research found a successful uptake in HN and HN-CHP technology with high level of predicted CO_2 savings (Day et al, 2007). Furthermore, CHP was reported as the most cost effective method for delivering CO_2 reductions in London (GLA, 2006). The 2008 London Plan revised the energy hierarchy to prioritise HN-CHP ahead of RE:

The Energy Hierarchy (GLA, 2008):

1. *Use Less Energy (Be Lean)*
2. *Supply Energy Efficiently (Be Clean)*
3. *Use Renewable Energy (Be Green)*

The 2008 London Plan also set a 20% CO_2 reduction target to be achieved specifically from onsite RE (Policy 4A.7). Where developments did not achieve the full target, they were required to demonstrate why it was not feasible before planning permission was granted.

2.2.3 The London Plan – 2011

The next amendment (GLA, 2011a) removed the onsite RE target from the policy and moved towards an overall CO_2 reduction target, which could be met through a combination of one or all stages of the energy hierarchy. However, the 20% onsite RE target remained an aspiration. The change from a RE target to overall reductions was a recommendation from research analysing the performance of TLP energy policies (Day et al, 2009). The research found that onsite CHP had in some developments reduced the opportunity for certain types of RE owing to conflicts of energy demands being met (ibid). TLP also outlined a pathway to zero carbon homes through incremental increases to the CO_2 reduction target (policy 5.2).

Policy 5.2 – Minimising Carbon Dioxide Emissions in Residential Buildings (GLA, 2011a p.141):

- *2010-2013 – 25% Improvement Beyond 2010 Building Regulations*
- *2013-2016 – 40% Improvement Beyond 2010 Building Regulations*
- *2016-2031 – 100% Improvement Beyond 2010 Building Regulations*

HN and CHP were again prioritised within the policy. To help the development of HNs the 'London Heat Map'[3] online tool was launched which provided an interactive map and database of existing and planned HNs. The tool provided developers and planners with local information to help evaluate the opportunity for HNs. To comply with policy 5.2, the map was to be utilised as part of the ES feasibility assessment. Figure 2.1 shows the heat map representation of annual fuel use for heating related to areas (KWh/m^2/year) in London.

[3] Available at: https://www.london.gov.uk/what-we-do/environment/energy/london-heat-map

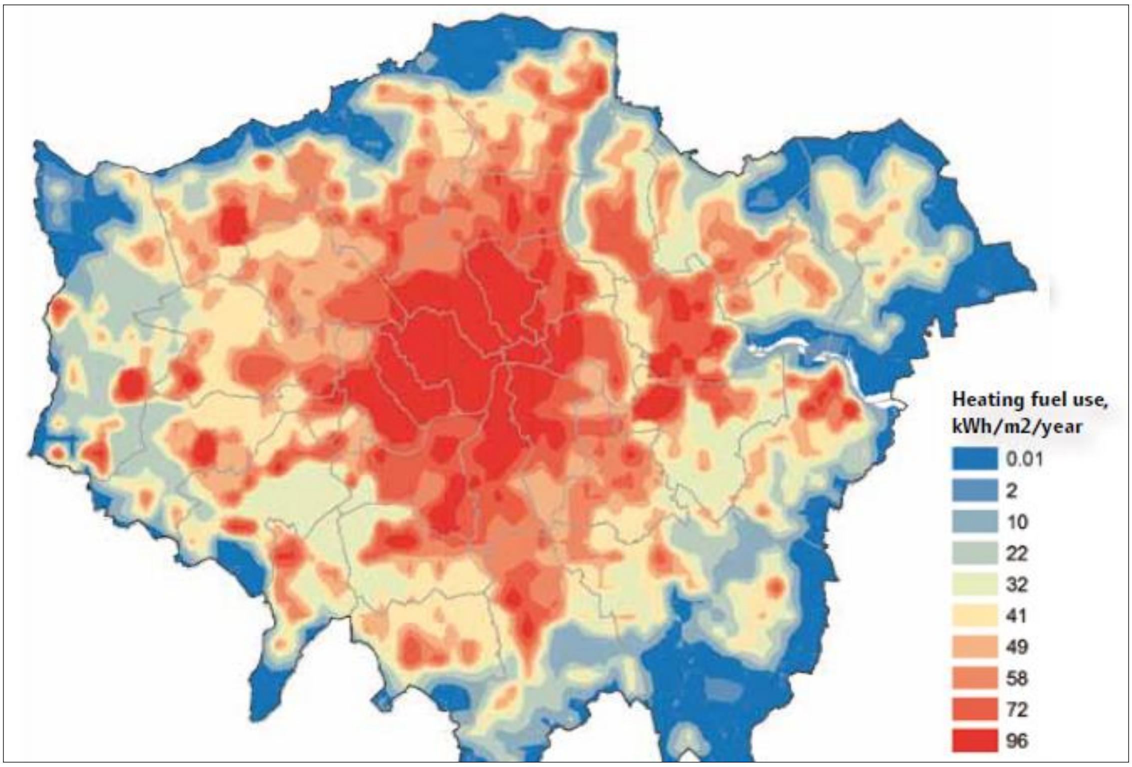


Figure 2.1: The London Heat Map – Annual heating fuel use in London (kWh/m^2/year) (GLA, 2011b)

Policy 5.6 also provided a revised ‘order of preference’ for the selection of heating and cooling systems. Individual fossil fuel systems such as domestic gas fired boilers were now excluded from the hierarchy altogether, suggesting that these technologies should not be considered:

Policy 5.6 - Energy Systems Hierarchy (GLA, 2011a p.148):

1. *Connection to Existing Network Heating or Cooling Systems*
2. *Site Wide Heat Network with CHP*
3. *Site Wide Heat Network*

2.2.4 The London Plan – 2016

The current plan (GLA, 2016a) constitutes the same structure and targets as the policies set out in the 2011 plan, with the addition of a new policy relating to electricity and gas supply (Policy 5.4A).

2.3 Preparing an Energy Strategy

Developers are required to demonstrate how their proposals have been designed to adopt TLP policies and the Mayor’s energy strategy. This is demonstrated through the creation and submission of an ES. The planning and technical guidance published by the GLA to guide developers on how to produce a policy compliant ES is now reviewed.

2.3.1 The Mayor's Energy Strategy

Policy 4A.8 and supporting paragraphs stated that Mayor's energy strategy *"sets out and explains how to apply a hierarchy to guide good decision-making and the consideration of developments proposals"* (GLA, 2004a p.165). The Mayor's energy strategy outlined London's framework for sustainable development but offered little in terms of specific design or technical guidance (GLA, 2004). The process and methodology of calculating a development's energy use (kWh/year) and CO_2 (kgCO_2/year) was not discussed in the Mayor's energy strategy or TLP. The energy hierarchy and the energy systems order of preference provided a basic guideline for prioritising specific measures, but offered no technical information or assessment method for the technologies it was recommending.

The Mayor's energy strategy encouraged developers to use BREEAM[4] assessment method, which at the time related to 'Eco-Homes' assessment for domestic buildings. An Eco-Homes assessment was a method of benchmarking a development's sustainability credentials against a number of categories including energy. To calculate the carbon footprint of a dwelling a Standard Assessment Procedure (SAP) had to be produced. A SAP is the calculation method for compliance with Building Regulations Part L1A (Raslan and Davis, 2012 p.306). The information from the SAP worksheet was added to the Eco-Homes 'CO_2 calculator tool' based on the BREDEM[5] 12, which provided a more 'comprehensive' figure of overall CO_2 (BRE, 2005). The SAP is a calculation tool for assessing energy use and CO_2 against a notional building regulations dwelling, it does not provide technical information regarding the energy efficient measures or technologies adopted – further detail regarding the SAP is provided in chapters 4 and 7.

2.3.2 The GLA Renewable Toolkit

In September 2004 a 'toolkit' was published by the London Energy Partnership '*London Renewables – integrating renewable energy into new developments: Toolkit for planners, developers and consultants*' (LEP, 2004). The publication was designed specifically to support planners, developers and consultants on how to implement the Mayor's climate change

[4] BREEAM – Building Research Establishment Environmental Assessment Method

[5] BREDEM – Building Research Establishment Domestic Energy Model

policies. The document offered advice on 'aesthetic issues, risks, reliability, and cost benefit analysis of renewables'. Furthermore, it provided information on 'successful' case studies and 'overcoming problems'. The toolkit was also designed to inform the forthcoming Supplementary Planning Guidance (SPG), which would be published in May 2006. However, the toolkit was not referenced in either TLP (GLA, 2004a) or the Mayor's energy strategy (GLA, 2004). It is therefore unknown how or if developers were directed to the toolkit.

Although the toolkit is predominately focused on RE, it does discuss the other two stages of the energy hierarchy including HNs and CHP. The toolkit discusses the requirements of CHP including economic viability (minimum run time 4000hrs/year) and the need for large constant heat demands (LEP, 2004). It identifies how this can be problematic with modern dwellings that have low heat demands owing to increased energy efficiency and that CHP is best suited to other building types (e.g. leisure centres) or mixed use developments with 'suitable' heat demands. The toolkit does not provide any further details on what constitutes a suitable heat demand or provide other resources for reference. The toolkit provides flow diagrams to highlight common issues that should be considered for each RE technology. It is made clear that these were simplified guidelines and further information and feasibility studies were required (ibid).

The methods available (as listed below) for calculating a developments energy demand and potential CO_2 savings are outlined. For dwellings, it was recommended that the SAP calculations were used. The differences between these calculation methods are discussed in detail in chapter 4:

- Published Benchmark figures
- Semi-empirical software models (SAP)
- Dynamic Simulation models

The toolkit provided substantially more detailed information than TLP or the Mayor's energy strategy. RE was discussed in detail providing the developers technology benefits and drawbacks. Furthermore, it described which building type and users are suited to each respective RE. However, as HNs and gas-fired CHP are not RE they are largely ignored and although the feasibility assessments are advocated no methods are described.

2.3.3 The Supplementary Planning Guidance – Sustainable design and Construction

The SPG – '*Sustainable Design and Construction*' was published in May 2006 (GLA, 2006a) and provides additional information to support the implementation of the TLP policies. The SPG provides a further descriptive analysis of the energy hierarchy, but references the '*London Partnership - Renewable Toolkit'* (LEP, 2004) for further detailed guidance on RE. Furthermore, for the first time, specific guidance regarding the format of ES was outlined. The SAP was confirmed as the method to be used to predict energy and CO_2 in residential buildings. A site's baseline CO_2 is to be taken as a building regulations compliant building. Table 2.2 details the key sections that should be included in an ES as defined in the SPG.

Table 2.2: Energy Strategy Format Guidance (GLA, 2006a)

Key Section	**Section Description**	**Calculation Required**
Executive Summary	Set out the key energy efficiency and design measures, the heating and cooling systems incorporated including: conclusions of CHP feasibility study and choice of renewables systems.	None.
Energy Demand Assessment	Heating, cooling and electrical demands are to be assessed and presented. The demands are used to identify 'technical feasibility' of RE.	Estimate energy demand (kWh/yr) and the associated CO_2 emissions ($kgCO_2$/yr). Calculated for each: • Baseline scheme • Final proposed scheme • Reductions related to RE
Energy Efficient Design Measures	The architectural and building fabric material measures are to be set out and demonstrate how they exceed Building Regulations Part L standards.	Calculation of the site's energy (kWh/yr) and CO_2 emissions ($kgCO_2$/yr) savings.
Heat and Cooling systems	Demonstrate how the Mayor's heating hierarchy has been applied and investigate the feasibility of CHP.	Calculate the energy (kWh/yr) and CO_2 emissions ($kgCO_2$/yr) from heating and cooling systems.
RE technology	A description and consideration of each RE. A scheme-specific justification must be provided where a 10% onsite reduction is not achieved.	Calculation of energy (kWh/yr) and CO_2 emissions ($kgCO_2$/yr) compared to scheme without RE.
Conclusions & Commitments	Outline how the fundamental principles of the energy policy, energy hierarchy and provision of RE have been adopted.	None.

The SPG was the first guidance document that provided developers with a format for what should be included in an ES. Throughout the planning policy and guidance documents developers are instructed to apply the energy hierarchy, which has been shown to prioritise HN-CHP over other RE technologies. However, the documents do not provide any technical guidance or methods of how to conduct a feasibility assessment. The SPG (2006a) does provide a reference to the CHP association (www.chpa.org.uk) among its list of further website resources. However, it does not reference this website or other CHP resource within the main body of the document. Furthermore, the registered URL **www.chpa.org.uk** is not relate to Combined Heat and Power or the construction sector (accessed 30.09.2016).

2.3.4 Energy Planning – GLA Guidance on Preparing Energy Assessments

In 2011 the GLA published a formal guidance document to provide further detail on addressing the energy hierarchy through the provision of an ES (GLA, 2011b). The guidance was updated in 2014 to coincide with the changes to Part L of the building regulations (GLA, 2014a). The guidance was further updated in 2016 with additional text aimed at clarifying the energy hierarchy (policy 5.6) and gave scenario based descriptions for where a CHP might or might not be considered appropriate (GLA, 2015a). These scenarios are outlined in figure 2.2.

The documents repeat the guidance given in the SPG (GLA, 2006a), that planning officers should secure the ES commitments through planning conditions. Planning conditions are applied to applications to *“enable development proposals to proceed where it would otherwise have been necessary to refuse planning permission”* (Ministry of Housing, 2014). This policy guidance is important in the context of this research, as it places a legal requirement on the developers to implement the measures outlined in the ES (unless the condition is modified or a new planning application is made). Therefore, the decisions regarding the type of technology and the scale of CO_2 reduction is set at an early stage of the project and will directly influence the decisions and actions taken through the remainder of the project. The accuracy of the assessment methods adopted by the designer and their technological perspectives that inform and justify their decisions, can therefore be considered crucial to the deliverable performance in practice. The GLA suggests that with the planning guidance available, energy should be fundamental to any new planning application (GLA, 2006a). However, the examination of the published guidance presented in this chapter has shown that policy directs the type of technologies selected, but provides very little substantive guidance on how to assess their expected performance.

The remainder of this section does not intend to provide an exhaustive review of the GLA energy assessment guidance. It examines the guidance specifically related to the assessment of a HN and CHP.

Once demand for energy has been minimised the assessment should demonstrate how the energy systems have been “*explicitly”* selected in accordance with the energy systems order of preference (GLA, 2011b, p.8). Reasoned justification should be provided where an energy system is not considered appropriate (GLA, 20011b; 2014a; 2015a). This guidance places a strict prescriptive procedure on how the designer’s should select an energy system and what criteria should be applied.

Figure 2.2 illustrates with a flow diagram the GLA guidance regarding the selection of energy systems from the London Plan 2016 energy systems order of preference (GLA, 2016a).

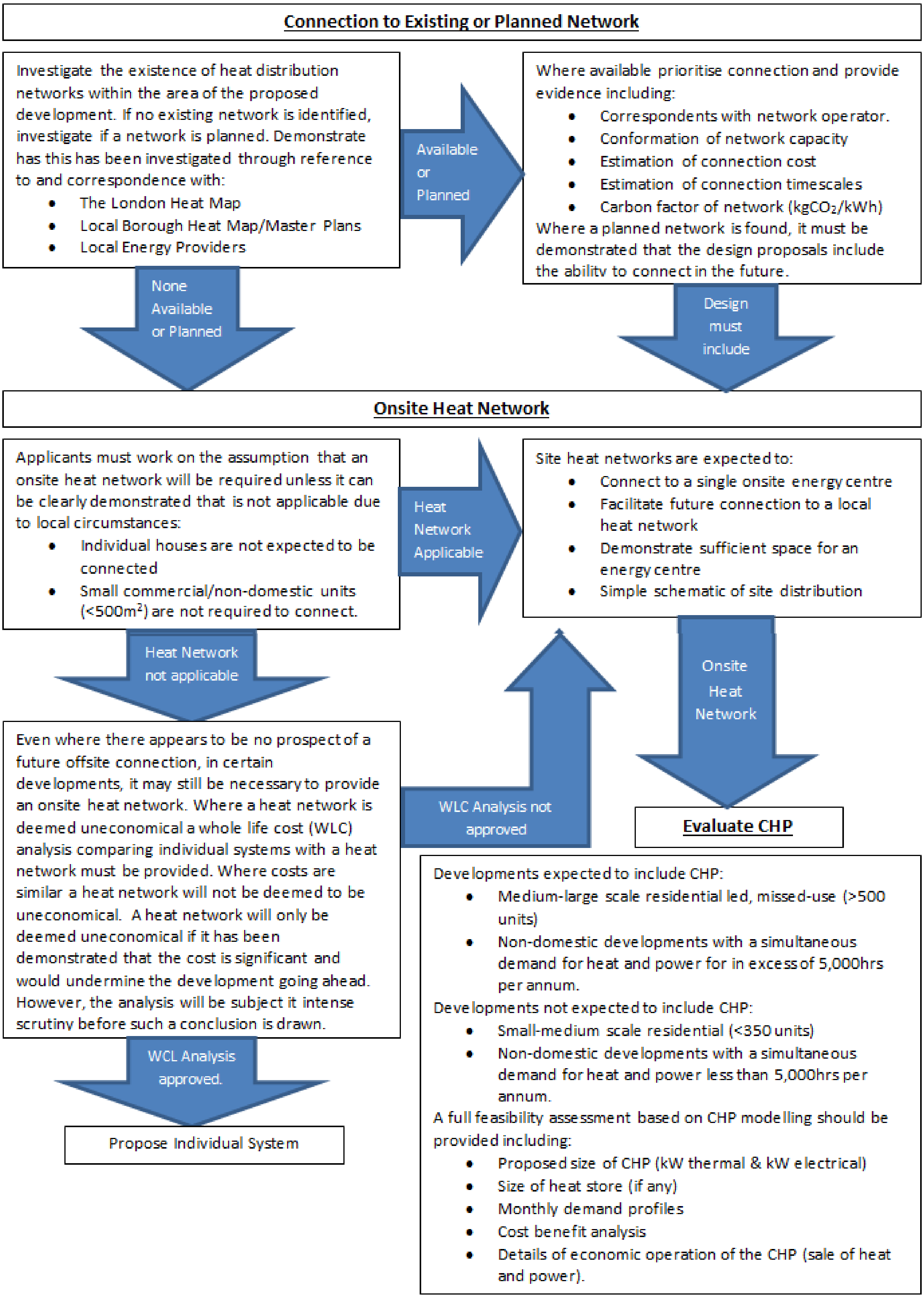


Figure 2.2: Flow Diagram of the GLA Guidance for the Selection of Energy Systems (adapted from GLA, 2016a)

The GLA also released guidance on the design of HNs, '*GLA District Heating Manual for London'* (DH manual) (GLA, 2013a). The DH manual was intended to provide guidance to the development and delivery of HNs in London. In order to retain flexibility in the planning and development of HNs the DH Manual was not published by the Mayor as a formal SPG. However, it is considered a standard that must be referred to (GLA, 2013a). The DH manual is reviewed in further detail in Chapter 3, here the guidance provided on feasibility assessment of HN-CHP is outlined.

The DH manual suggests that a viability assessment (cost and financial implications) as well as a feasibility (engineering and practical constraints) should be required by the LPA (GLA, 2013a P.66). The following is expected to be provided within the viability and feasibility assessments:

- *The proposed development's size, heat loads, energy demands and land use mix.*
- *Distance from other HNs including the presence of physical barriers (e.g. railway lines)*
- *The cost of connection and impact on system financial viability.*
- *Evidence of correspondence with other nearby buildings to create a local network.*
- *Land use mix of local area and density.*

Table 2.3 outlines the quantitative and descriptive guidance provided by the GLA documents on the appropriateness of HN and CHP; case study examples referred to by the GLA are also provided in the table.

Table 2.3: GLA Guidance on Heat Networks and CHP

Quantitative Guidance	**Descriptive Guidance**	**Reference Examples**
	The London Plan 2011 (GLA, 2011b)	
None.	• Multiple buildings or where building density is sufficient. • Large scale developments should undertake feasibility assessment. • CHP optimised to thermal load profile.	Existing Networks: • Olympic Park • Citigen Plimlico • Barkantine CHP • Whitehall DHN • Bunhill DHN • UCL & Bloomsbury CHP Examples of Planned Networks: • Vauxhall Nine Elms Battersea • Euston Road Scheme

<table>
<tr><td colspan="3">The London Plan 2014 (GLA, 2014a)</td></tr>
<tr><td>• Whole Life Cost (WLC) analysis template
• Small purely residential development (<300 dwellings) is not expected to include onsite CHP.</td><td>• Well-designed heat networks and individual boilers have similar WLC for high density developments.
• Where WLC are similar a heat network will not be considered uneconomical.
• Provide a heat network where a district network could be provided in the future.</td><td>Additional Existing Examples:
• Kings Cross
• SELCHP
Additional Planned Networks:
• Vauxhall Nine Elms
• Royal Docks</td></tr>
<tr><td colspan="3">The London Plan 2015 (GLA, 2016a)</td></tr>
<tr><td>Developments expected to include CHP:
• Medium-large scale residential led, missed-use (>500 units)
• Non-domestic developments with a simultaneous demand for heat and power for in excess of 5,000hrs per annum.

Developments not expected to include CHP:
• Small-medium scale residential (<350 units)
• Non-domestic developments with a simultaneous demand for heat and power less than 5,000hrs per annum.</td><td>Developments expected to include CHP:
• Hotels
• Hospitals
• Leisure Centres
• Student Accommodation
• Prisons.
Developments not expected to include CHP:
• Offices
• Schools</td><td>None.</td></tr>
</table>

The GLA's energy planning guidance (GLA, 2011b; 2013a; 2014a & 2015a) provides a formal set of guidance on the structure, calculation method and description of addressing the energy polices and applying the energy hierarchy through the provision of an ES. The guidance reaffirms the ES as a compulsory document for all new developments. Furthermore, directs planning officers to secure the commitments through planning conditions. These actions secure the ES as an influential document throughout the project duration. The developers are committed to follow through with the proposals committed at planning stage. In projects procured through a 'design and build contract' the planning approval is often achieved prior to the involvement of the detailed designers and main contractors, who are ultimately responsible for implementing the strategy. Therefore, they are reliant on the accuracy of the ES assessment to provide deliverable performance in practice.

The GLA suggests that there is sufficient information available through its published policy and guidance documents for designers to complete an appropriate assessment of proposed measures. The most recent guidance recognises the technical and economic complexities of the HN and CHP, suggesting that individual houses and small commercial units are not suitable for connection to a HN (with or without CHP) due to the low heat density and costs of connection (GLA, 2014a; 2015a). Furthermore, the economic complexities and burden of managing CHP export sales due to the small landlord electricity are recognised. At these small scales energy service companies (ESCOs) are considered not be generally active (ibid). The GLA guidance (2015a) presented example descriptions of development types where a CHP would not be expected to be installed. These are defined as small residential developments (<500 dwellings) and non-domestic developments with low demand for heat and power (< 5,000 hours per annum) in areas where there are no planned DE networks. The increased level of information provided within the guidance documents suggest that the GLA is recognising the associated issues (potentially received through industry feedback) and are adapting planning guidance to provide clarification to planning officers and applicants.

The next section reviews the body of research that has been conducted relating to the outcomes of TLP energy policy.

2.4 Analysis of the London Plan Energy Policies

The body of academic research and industry study that exists relating to the evaluation of TLP energy policy is now examined. This includes the official annual monitoring reports (AMR) of the GLA and LPA, as well as academic research. The previous sections of this chapter have demonstrated that policies at all levels of government are intended to deliver in real terms CO_2 reductions. As well as increase the implementation of energy efficient measures, HN, CHP and RE technologies. Therefore, in the context of this research it is important to understand how the current policy is being evaluated, the findings, and how these findings influence policy change through evidence-based planning.

2.4.1 Monitoring the London Plan Energy Policies

A study by Day, Ogumka and Jones (2009a) claimed that the early energy policies implemented by the GLA were successful and were responsible for proposed savings of 135 ktCO_2/year compared to scheme built to a Building Regulations compliance baseline. Their study examined ES documents that were referred to the GLA between 2004 and 2005. Figure 2.3 shows the analysis by Day et al. (2009a) of 113 ES documents outlining the cumulative CO_2 savings and individual savings from energy efficiency, CHP and RE (savings from HN are not shown). From figure 2.3, the significant increase in reported cumulative CO_2 savings following the implementation of TLP is evident.

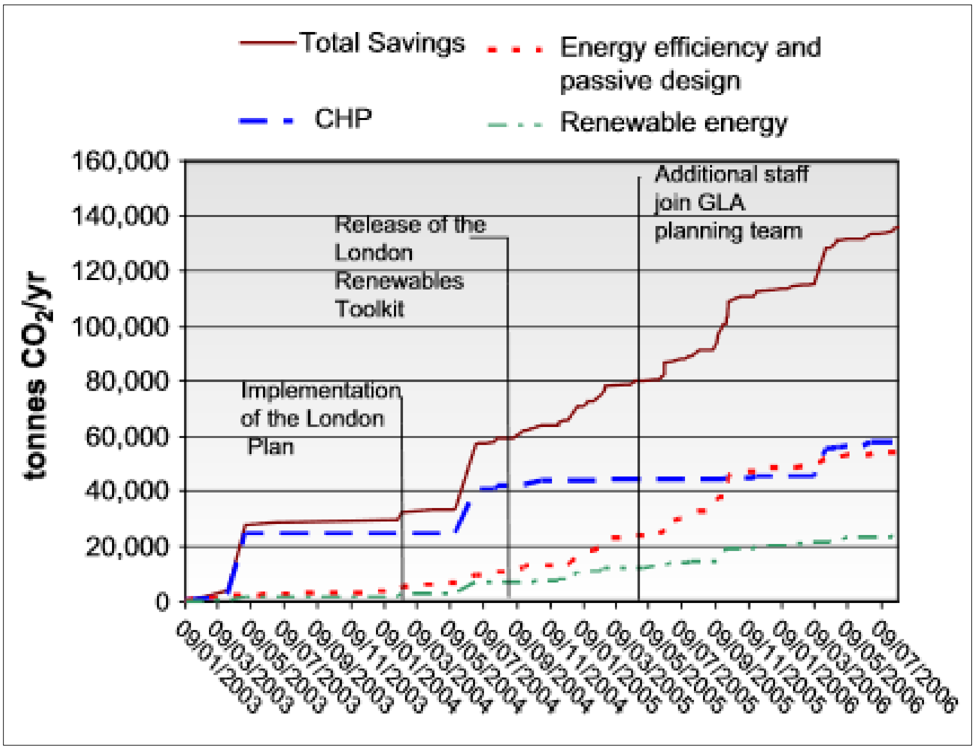


Figure 2.3: Cumulative CO_2 Savings (2003-2006) based on 113 Developments (Day et al, 2009a p.2020 fig.7)

Day et al. study also concluded that applicants initially struggled to meet the RE target outlined in the 2004 London Plan (2009a). However, the authors did not see this as a failure of the policy, citing the increased CO_2 savings from energy efficiency measures and CHP being linked to the lower RE contribution to overall reductions. Most developments achieved the RE reduction target from 2005 onwards. Day et al. suggested two key interventions resulted in the increased trend. Firstly, the publication of the LEP's *Renewables Toolkit* providing a standardised methodology for assessing energy and CO_2 savings. Secondly, the introduction of more staff to the GLA, which increased the level of capacity and knowledge of renewables. They also suggested that owing to more planning staff, the policy targets could be more rigorously enforced (ibid).

Their research also concluded that the policy was developing good engineering design skills and knowledge within London (2009a, p.2021). For instance, the regulatory pressure was seen as forcing some of the conflicting technological issues to be resolved and leading to 'good quality' solutions. However, it was also recognised that some developers often complained that the policies were too prescriptive (ibid). This was also felt by participants of the EiP, who argued for greater freedom to allow developers to decide how to use technology to achieve targets (Shepley, Langton & Nixon, 2007). Research by Rydin, Amjad and Whitaker (2007) also found little evidence to support the view that planners, in particular in local boroughs, were increasing competency levels in environmental construction. These research studies have suggested that prescriptive policy can restrict the choices available to designers. The freedom for developers to apply independent technical arguments and decisions is an important factor to consider in the context of this research, as well as the direct influence that policy might have on the types of technological measures being selected.

The second stage of analysis was conducted between November 2006 and June 2009. This period encompassed significant changes to the London Plan energy polices. In September 2006 a draft *Further Alterations to the London Plan* (FALP) was published for consultation, it included the proposed changes to the energy hierarchy (prioritising HN and CHP) and a target of 20% (increased from 10%) onsite CO_2 reductions to be provided from RE. Although not formally adopted until 2008, by 2007 these draft measures had gained more weight within planning decisions (Day et al, 2009). Furthermore, additional staff joined the GLA energy team in 2007. Day et al (2009) provided an analysis of 147 ES documents from strategic applications referred to the GLA. The conclusion was that TLP had been successful in *"significantly reducing energy consumption and CO_2 emissions in new developments"* (ibid, p.4) and savings amounted to 116 $ktCO_2$/year. Figure 2.4 demonstrates the significant growth in CO_2 savings during a 15 month period following the draft publication of the FALP. This included further growth in savings from CHP, as well as RE. Day et al. attributes these increased CO_2 savings directly to the policy changes (ibid).

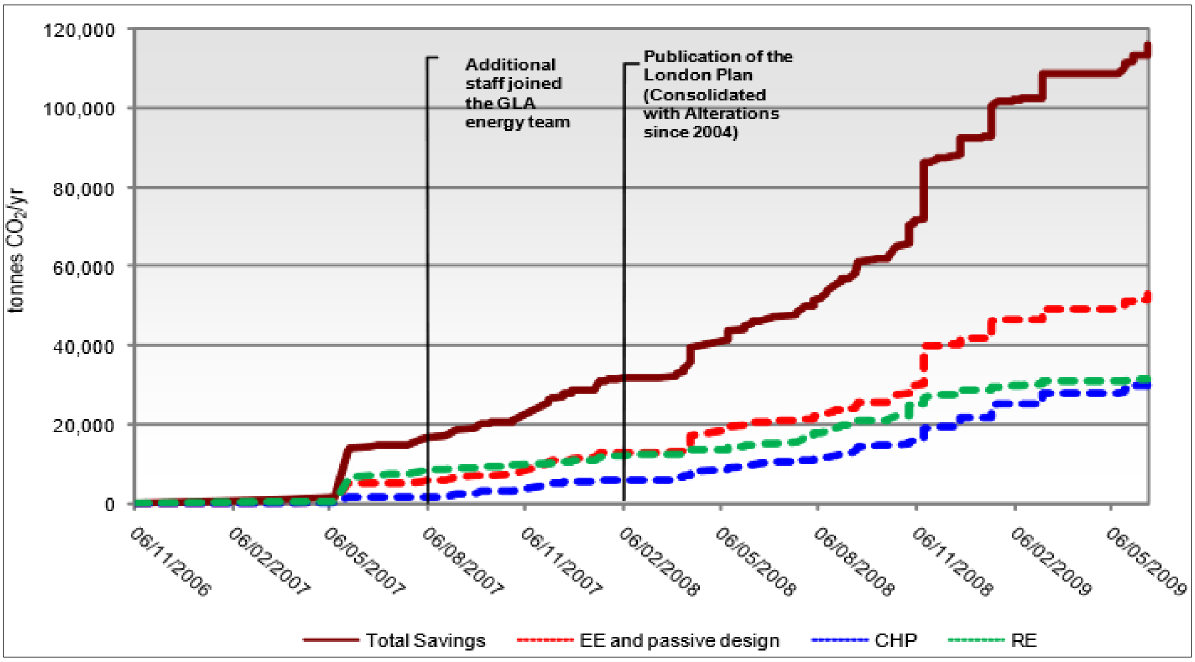


Figure 2.4: Cumulative CO_2 Savings Over Time (2006-2009) from 147 Developments (Day et al, 2009 p.13 fig.5)

Figure 2.5 illustrates the average percentage CO_2 saved per development from CHP over time. The figure shows that the average percentage increased significantly between 2006 (6%) to 2009 (15%). Figure 2.6 illustrates that over the same period the average percentage saving from RE per development declined. Day et al. attributed this decline to the larger savings secured from CHP, which limited the amount of energy that RE could offset. These findings identify the speed of technological adoption from RE to CHP following the changes to TLP energy hierarchy prioritising CHP over RE. The study also identified 49 developments that did not include CHP, suggested this was owing to the development size or insufficient heat demand (Day et al, 2009).

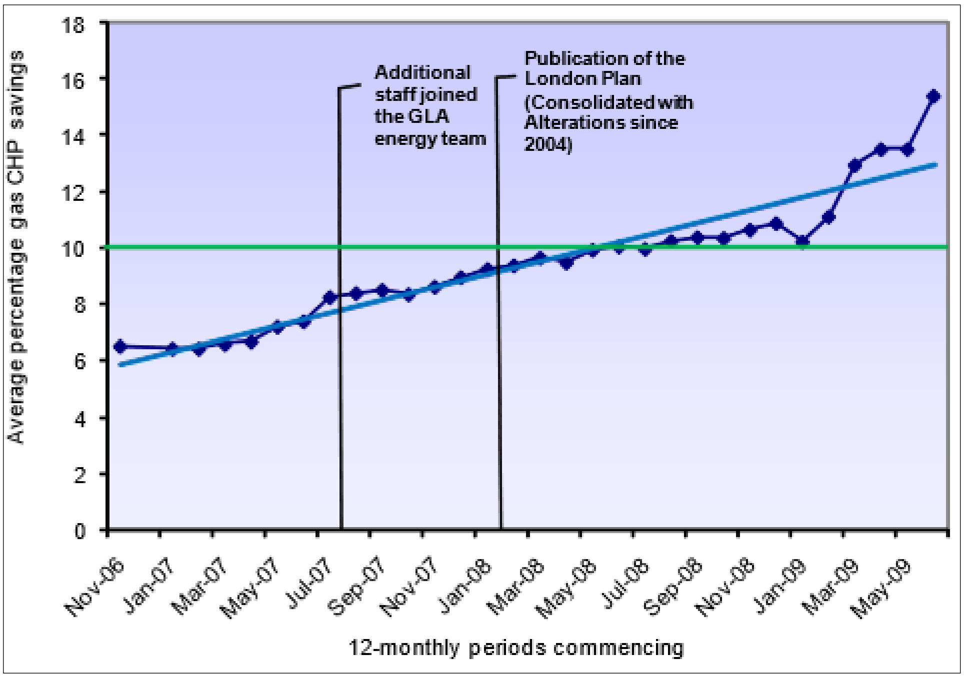


Figure 2.5: Twelve Month Average Percentage (%) from CHP (147 Developments) (Day et al, 2009 p.19 fig.13)

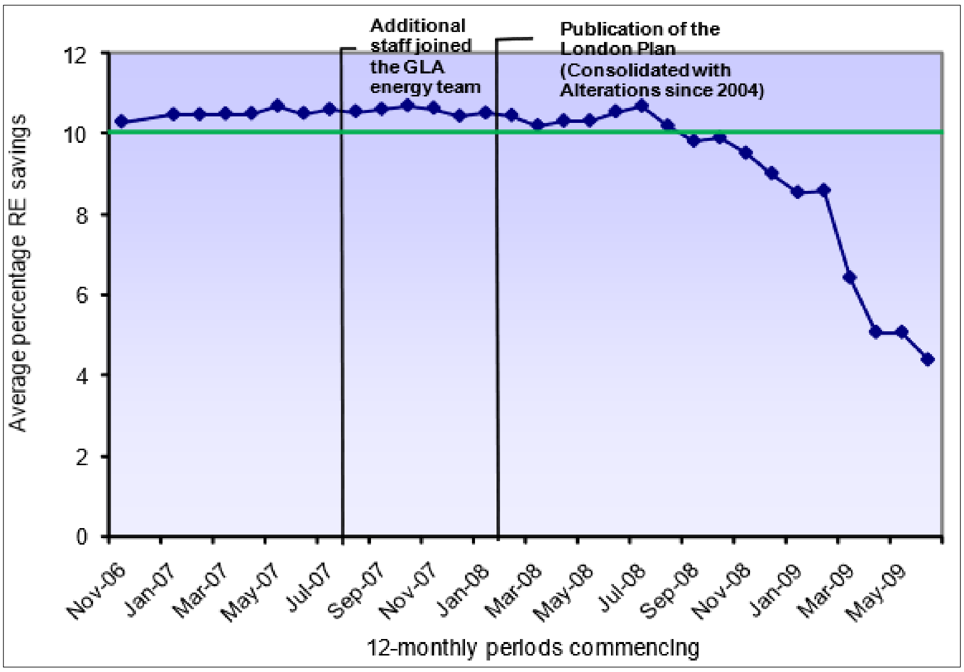


Figure 2.6: Twelve Month Average Percentage (%) from Renewables (147 Developments) (Day et al, 2009 p.23 fig.18)

Despite the average percentage of RE reduction observed from individual developments, the overall uptake and CO_2 saved from RE is shown to have increased significantly (figure 2.4). What can also be observed from the research by Day el al (2009), is the apparent influence that policy had on the type of technology selected. Figures 2.5 and 2.6 demonstrate the increased savings reported from CHP compared to RE, corresponding to the change to the energy hierarchy prioritising CHP. The apparent influence of policy can also be observed in type of RE technology selected. Figure 2.7 demonstrates the cumulative number of installations of RE from 2004 to 2006 and 2007 to 2009. In the earlier period (2004 to 2006) Solar Thermal (ST) can be seen as the most frequent technology adopted, whereas for the following period (2007 to 2009), which encompassed TLP policy change from 10% to 20% RE reduction target, ST installations reduced significantly compared to other technologies. One inference that could be drawn from this data is that an individual ST system had a lower CO_2 savings potential compared to other larger scale technologies, such as biomass (figure 2.8).

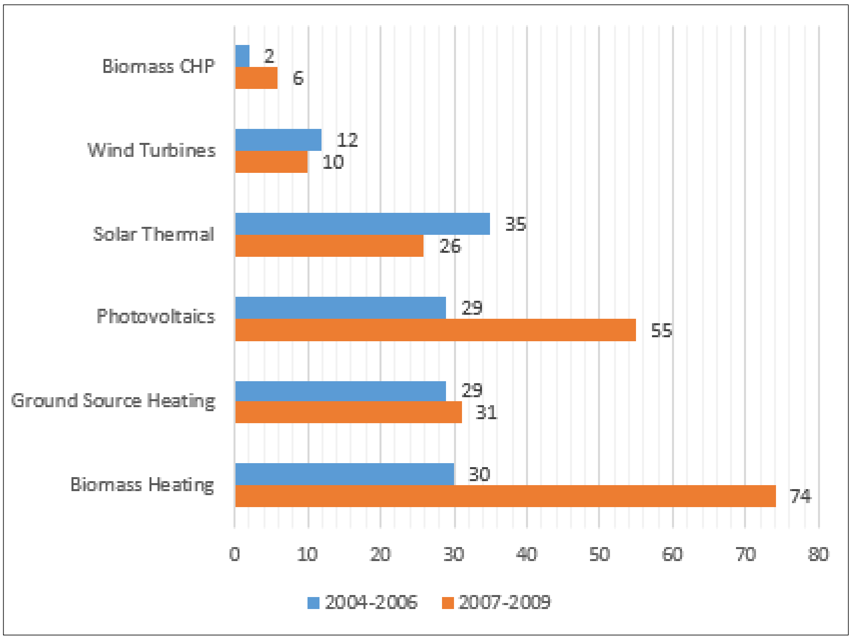


Figure 2.7: Cumulative Number of Renewable Energy Installations
(adapted from Day et al, 2007; 2009)

Figure 2.8 demonstrates the difference in total cumulative CO_2 saved from each technology (gas CHP not included). Biomass heating is reported to have saved considerable more (approximately six times) CO_2, compared to photovoltaic despite having only a third more installations. ST is also shown as having the lowest cumulative savings of all the included technologies, despite having a higher number of individual installations. This data suggests that RE technologies could have been selected based on their CO_2 saving potential or in other terms their policy compliance potential. The inference being that the increase in RE policy target (10% to 20%), influenced the type of RE technology selected, as technologies with low CO_2 savings potential would not achieve the policy target and were therefore less likely to be selected.

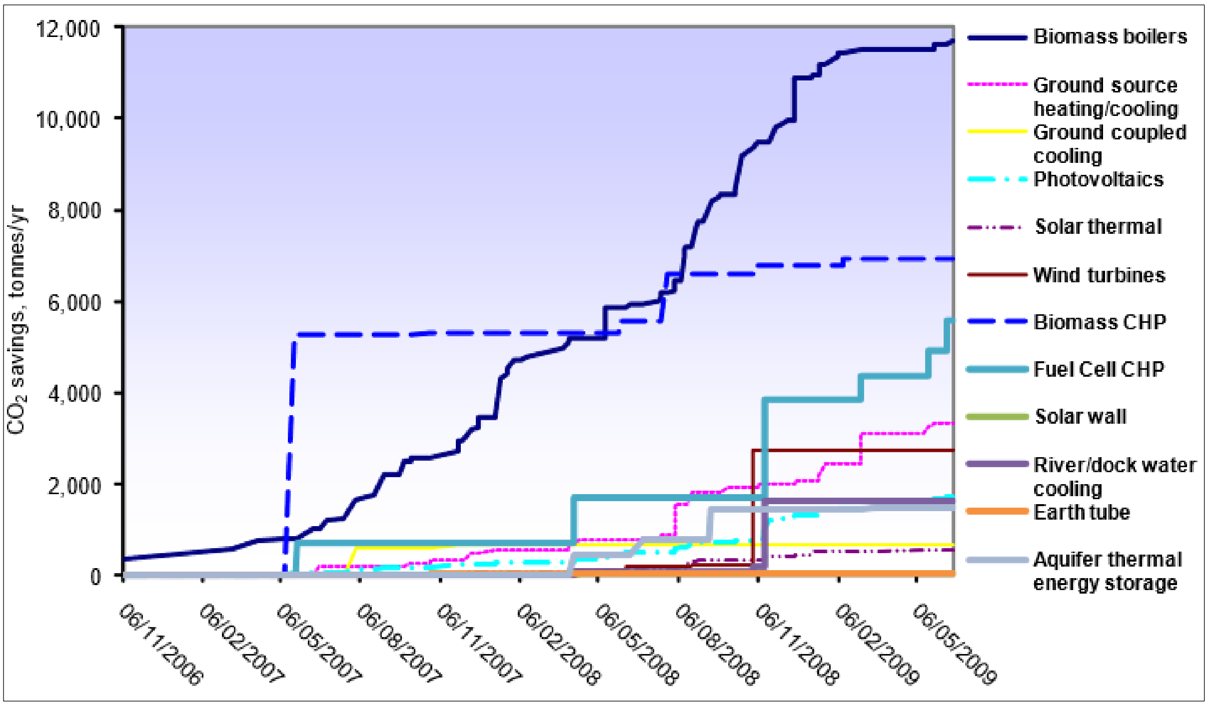


Figure 2.8: Total Cumulative CO_2 Saved by Renewable Energy Technology (Day et al, 2009 p.28 fig.24)

In 2010 the GLA started to conduct its own analysis and published AMR, reporting on the outcomes of the TLP policy based on ES documents submitted to the GLA. Data from the AMR reports (GLA, 2011 to 2017) is represented in table 2.4. The table illustrates the changing trends in the number of installations by RE type. In the 2011 publication of TLP the RE target was replaced with an overall percentage reduction in CO_2 target. Following this policy change the consistent trend of proposed biomass installations observed between 2006 and 2009 was quickly reversed (table 2.4). The GLA suggested the decline was due to air quality concerns (GLA, 2014). However, the data could also indicate that this decline was related to the change in RE target, allowing RE with lower CO_2 saving potential (e.g. PV and heat pumps) to be selected as part of an overall CO_2 reduction strategy, this is supported by the increase of other technologies (table 2.4).

Table 2.4: Renewable Technology Trend between 2011 and 2017 (GLA, 2011; 2012; 2014; 2015 & 2017)

RE Technology	**Number of Proposed RE Installations per Year**						
	2011	2012	2013	2014	2015	2016	2017
Photovoltaic	60	107	123	98	111	104	100
Biomass	14	7	8	2	4	1	0
Heat Pumps	19	21	27	43	25	42	41
Solar Thermal	10	6	12	9	4	3	2

Examining the data related to the number of HN and CHP installations reveals a significant proportion of developments planned to install either HN (without CHP) or HN-CHP. The findings show that CHP was reported to have the highest contribution to CO_2 reductions (Day et al, 2009; GLA, 2010; 2011; 2012; 2014; 2015; 2016). Table 2.5 presents the year-on-year projections of uptake in HN-CHP. The findings also demonstrate that HN-CHP (*be clean*) are accountable for approximately two thirds of all CO_2 reductions, significantly higher than the other stages of the energy hierarchy (table 2.6).

Table 2.5: Planned uptake in HN and CHP capacity in London from Strategic Developments submitted to the GLA (2006 to 2015)

Year	**Percentage of New Dwellings Connected to HNs**	**Planned New CHP Electrical Capacity (MWe)**	**Estimated Savings from CHP (Tonnes CO_2 / Year)**
2006-2009*	No Data	12.4	25,331
2010	95.81%	28	36,392
2011	96.71%	17	32,398
2012	94.85%	29	29,447
2013	95.18%	25	29,168
2014	91.66%	20	27,634
2015	89.81%	32.02	31,696
Total	-	163.42	222,066

*data from 113 developments (Day et al, 2009)

Table 2.6: CO_2 Percentage Reduction for Each Stage of the Energy Hierarchy between 2011 and 2015 (GLA, 2011; 2012; 2014; 2015; 2016)

Energy Hierarchy Stage	**Percentage Reduction in Onsite CO2 emissions**				
	2011	**2012**	**2013**	**2014**	**2015**
Be Lean	1%	5%	9%	13.6%	7.4%
Be Clean	25%	23%	21%	19.6%	20.7%
Be Green	9%	8%	6%	5.7%	5.7%
Cumulative Reduction	33%	36%	36%	38.9%	33.8%

It must be recognised that GLA monitoring reports only consider the strategic[6] applications submitted to the GLA, they do not include the non-strategic major[7] applications received by LPA. Section 2.3.4 identified that the GLA guidance does not advocate the use of CHP for small residential only developments of less than 350 dwellings and similarly does not expect HNs to be provided in low density developments where a future district heat network is not planned. It could therefore be expected that there would be a large uptake among strategic developments at a GLA level and a lesser extent with smaller local developments at LA level. However, there is evidence from LPA's (see below) that HN and CHP are commonly being adopted at a non-strategic level.

A review of recently published AMR documents (GLA, 2011 to 2016) for a range of LPAs identified that very few have reported on the outcomes of their energy policy. Either the relevant energy policy is not mentioned or some cite a lack of available data to provide a report. Examples from LPAs that have published relevant information have identified the success in the increased uptake in both HNs and CHP, as well as the associated CO_2 reductions.

The London Borough of Ealing reported that for the period of 2012 and 2014, 25% of major applications identified CHP as the most feasible and viable technology to achieve the CO_2 reduction targets (Ealing Council, 2012; 2014; 2015). Islington Council for the period of 2012 to 2014 reported a "majority" and "increasing number" of applications containing an onsite HN (Islington Council, 2015; 2016). Hackney Council (2011) reported that CHP is likely to play a significant role in achieving future reductions in CO_2. While Hammersmith and Fulham

[6] Strategic Planning Applications – applications of strategic importance to London (including developments of: >150 dwellings; >30m height; on green belt land)

[7] Major Planning Applications – new developments consisting of 10 dwellings or more.

(2015) stated that major developments were now most likely to achieve the biggest CO_2 savings through CHP.

The consensus from the available studies is that TLP energy policies have been and continue to be successful. Even where individual policy targets have not been achieved, it has been perceived as a consequence of targets being surpassed in other policy areas. The strategic aim of TLP is to reduce energy consumption and CO_2. The research studies are unequivocal that this has been achieved and furthermore that the reductions are near to or above the levels targeted. The critical finding from the examination of these reports is the significant contribution to CO_2 savings reported from HN-CHP. Approximately two-thirds of all CO_2 reductions at a strategic level are attributed to HN and CHP. The stated success of TLP policy is considered as real terms CO_2 reductions, as well as successful increase in LZC technology uptake (GLA, 2016). One can therefore argue that the success of TLP energy policy is directly and predominately associated with HN-CHP. Furthermore, the ability of these technologies to deliver the performance in practice, is central to the credibility of the planning system as a mechanism for delivering CO_2 reductions through the built environment.

The evaluation of the evidence presented in this chapter suggests a direct link between the policy and the type of technology being most predominately adopted by developers. The observed uptake of specific technologies could question whether an ES is actually an independent technical assessment based on the unique technological, social and economic aspects of individual developments. The existing available analysis of the TLP energy policies has utilised the ES documents as the main source of evidence. The statements and quantitative figures presented in these documents are taken as empirical data of the types of technologies being installed and the successful reductions in $CO_{2.}$ However, the use of the ES documents as a form of 'evidence-based' policy has been questioned, this is discussed in the next section.

2.4.2 Evidence Based Planning Policy in the London Plan

The Planning and Compulsory Purchase Act (2004), required local development plans to be tested and justified against appropriate evidence. Evidence-based policy is seen as one of the reasons why technology is gaining more prominence in the planning process. Within spatial planning, evidence is weighted towards quantitative data and statistics (Rydin, 2010). Rydin (2010) argues that the emphasis on evidence does not necessarily lead to greater engagement between policy and technology. Rydin (2010) describes evidence as the presentation of information that may not have a particular content and it is the rhetoric used that constructs it as 'evidence'. Krizek, Forysth and Slotterback (2009) share this caution of what constitutes valid evidence, but recognise that there is a valuable role for research-generated evidence to inform decision making.

Any alterations to TLP must sit through an EiP. In the case of the 2007 FALP, the participants of the EiP were not convinced by the presented 'evidence'. The two studies submitted as evidence were undertaken after the policy had already been introduced and therefore seen as post-justification of the policy rather than being part of the policy making process (Rydin, 2010). This is an example of the use of rhetoric to construct evidence, where participants believed the evidence was an 'act of due-diligence' designed not contradict the policy, rather than a 'sound evidence base' (ibid). Although much emphasis was put on the use of case studies in the evidence, these were not seen as conclusive. Rydin (2010 p.253) survey of participants, found that they agreed that the evidence was weak, citing that an ES does not provide data on performance in practice. It must be recognised that some participants felt the studies where valuable, provided independent evaluation, and described them as professional and helpful for engaging stakeholders. Ultimately, the two studies helped underpin the support of the FALP. However, in the EiP panel report the reservations over the evidence presented was openly stated (HBF, 2007).

Despite these reservations similar evidence was presented at the next EiP for the FALP 2011, where a 'steeper trajectory' of CO_2 reduction targets were proposed (James, 2011). The EiP panel did not believe that the evidence presented a robust case for adopting steeper targets for smaller developments. The panel acknowledged and recommended that the steeper targets should apply only to strategic level developments. However, this recommendation was not accepted in the Mayor's response, which stated that it is the legal role of the TLP to set policy agenda at major development scales, not just strategic level (ibid). Furthermore, to limit the application of targets only to strategic applications would severely weaken the ability of LPAs to seek significant contributions to CO_2 reductions. The reservations expressed over the evidence presented was not addressed in the Mayor's response(ibid). The EiP panel also recommended adding further detail to the definition of feasibility assessment for HN and CHP, this was to include economic analysis regarding the cost to the developer and end-user. This recommendation was also not accepted, as in the view of the

Mayor, it could lead to a ‘too simplistic’ concept of cost analysis and defeat the objective of the policy to increase DE (ibid).

It is clear that there are concerns with defining the current EiP information as evidence-based policy. There are parallels that can be drawn with research by Packwood (2002) in her evidence-based review of education policy. For example, Packwood argues that it would be more accurate to refer to the practice as ‘evidence-informed’ policy, as policy is determined by more than research evidence alone. Economic and strategic factors, as well as practitioner knowledge were all expressed by participants of Rydin’s (2010) study as missing from the evidence presented to the EiP. Furthermore, examples of dismissing evidence that does not suit the preferred outcome is another commonality; participants of the EiP felt that the statistics presented showed that the existing policy target were already difficult to achieve, rather than supporting the GLA position to increase the target (ibid, p.253). Finally, who should disseminate the research evidence is a problem that is identified in both studies. Rydin (2010) identified that energy policy brings a whole new range of technological questions into the remit of the planning system, stretching the boundaries of traditional planning expertise. The EiP showed that there was a greater emphasis applied to consultants as repositories of expertise (ibid p.253).

The evolution of TLP energy polices examined through EiP can be argued to lack the credible evidence to construct knowledge and inform decision-making. The use of an ES as a source of evidence has been questioned by successive EiPs, however, this presented ‘evidence’ has continued to underpin the support and implementation of successive and more far reaching policy. Several research studies have argued that the ESs do not provide evidence on energy consumption in practice, that the performance of specified technologies once installed and operational must be assessed (Day et al, 2007 p.4; Day et al, 2009 p.2020; Keirstead et al, 2010 p. 4875; Rydin, 2010 p.253).

“What has been missing hitherto is evidence that these designs have actually been put into practice and the real carbon savings are resulting” – Day et al (2010)

The study by Day et al (2010) investigated 25 built developments to compare the installed technology with the ES intent. The study concluded that in terms of; number of installations, capacity installed, and CO_2 saved, the original ES intent was not achieved. However, the difference was small. The authors acknowledge the disappointment of the sample size and expressed the difficulties due to a lack of monitoring and reporting against planning conditions. Although Day et al (2010) provides evidence on the number and capacity of technologies installed, one can argue it does not meet the call for evaluation of performance in practice and actual CO_2 savings. The data for CO_2 saved was either provided directly by the developer or calculated using CO_2 emission factors and installed capacity (MW). The savings were not based on any formal post occupancy evaluation or metered data.

Adopting ES documents as a evidence of delivered savings in practice and 'desk-top' post-occupancy evaluation approach can be seen as a continuation of the 'Merton Rule'[8] success storyline as described by Rydin (2010 p.254) that is, that an installed LZC technology results, by definition, in CO_2 reductions. Accepting such storylines as evidence constructs knowledge informed by 'outcomes' rather than critical 'evaluation'. As suggested by Rydin (2010, p.251) *"evidence is a potential form in which knowledge can be constructed; how it becomes constructed in specific circumstances is a matter for empirical research"*. Evaluation and Feedback is an important step when forming policy, as described by Newton and Van Deth (2005) in their six-stage policy cycle.

2.5 Informing Local Energy Policy

Section 2.2 described the evolution of TLP energy policy. Section 2.4 analysed how AMR's have been used as an evidence base to inform and justify more ambitious policy targets. This section engages the academic research related to the formation of local policy. To understand how a policy is formed and how the analysis outcomes ('feedback') can inform the next iteration of the policy. Newton et al (2005, p.318) suggest that *"almost every public policy has its unintended and unanticipated side effects, which then become another problem for public policy. The result is an endless cycle of policy and decision making that tries to solve both the new problems of the world and also the side effects of old policies".* How this relates to the context of TLP energy policy is considered.

2.5.1 The Public Policy Cycle – The Six Stages

The process of creating local policy has been described by Newton et al (2005) as a six-stage 'policy cycle' (figure 2.9). The cycle begins with a public problem or objective that a policy must resolve (agenda setting). An appropriate course of action (decision making) and

[8] Merton Rule – policy devised by a planner at the London Borough of Merton, requiring that a percentage (10%) of the energy needs of a new building or development be met via onsite renewable energy technology.

method (choice of means) are then chosen. These are then put into action (implementation), which results in specific consequences (outputs and outcomes). These are analysed and conclusions are drawn for further actions (evaluation and feedback).

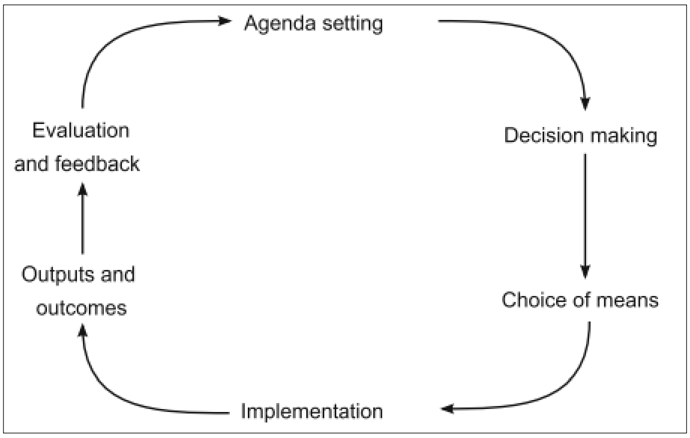


Figure 2.9: The Public Policy Cycle (adapted from Newton et al, 2005 p.319)

Table 2.7 applies the six-stages of the policy cycle to examine the formation of energy policy in London. Existing research related to urban energy policy and TLP is used to present a view of the energy policy cycle within the GLA.

Table 2.7: The Public Policy Cycle Presented in the Context of the London Plan Energy Policy

Agenda setting - 'Decide which issues/objectives to prioritise'
In the UK much of the national debate regarding energy is dominated by security of energy supply, fuel costs and climate change; however, Keirstead et al (2010) found via stakeholder interviews that within London not all of the main national themes were being represented (e.g. energy security and fuel poverty). These wider issues were seen as a matter for central government and that certain issues could only be 'managed' at local level owing to limited local powers (Keirstead et al, 2010, p.4873). Yet the agenda of climate change is seen as aiding a wider array of local goals, such as: fiscal savings, increased labour, economic stimulus, and reducing air pollution. The idea of LPA favouring agendas that have inter-related goals is supported by Rydin et al (2007, p.363). This agenda is set out in the Mayor's vision for London: *"A city that becomes a world leader in improving the environment locally and globally, taking the lead in tackling climate change, reducing pollution, developing a low carbon economy and consuming fewer resources and using them more effectively" – GLA (2016, p.176).*
Decision Making- 'Decide what actions to take'
Public consultations are the common method to solicitor stakeholder opinion of proposed policy. Consultations play an important role for engaging expert opinion and knowledge. The GLA consult on changes to TLP through an EiP. However, in the case of the London Energy Strategy (GLA, 2004) the consultation was seen as a promotional tool of the GLA's work on climate change rather than expert engagement. Pasimeni et al (2014) is of the view that local policy decision-making needs to be an *"interactive form, where communication processes such as bargaining, negotiations and arguing are seen as essential elements in policy-making*". Rydin (2010 p.250) found that many participants were 'frustrated' by the lack of debate. Low response rates are also cited as a potential issue of consultations, the Mayor's Energy Strategy (GLA, 2004) received a response rate of only 1.7% (Keirstead et al, 2010, p.4873). The analysis of the EiP has shown that in London the consultations have lacked the credible evidence or expert debate to inform decision-making, considering only the ES documents submitted in a planning application. Analysis of the EiP have shown that much of the feedback received from stakeholders has not been incorporated by the GLA (James, 2011).
Choice of means - 'The appropriate means to be used to achieve the course of action'
At a national level there is a wide range of tools that can be used to enact policy, including: direct service provision (although energy services are now privatised), setting of market conditions (e.g. taxation and incentives), regulation standards (e.g. Building Regulations) and public awareness and encouragement campaigns. Whereas LPA have limited control over these areas and therefore tools are restricted mainly to public awareness campaigns, financial grants and planning control. Keirstead et al (2010, p.4874) argue that with planning control the question is how best to implement policy and evaluate their performance against desired goals. TLP energy policy provides a set of goals (e.g. CO_2 reductions targets) and prescriptive measures to achieve them (e.g. the energy hierarchy). The implementation and evaluation of the policy is achieved through the creation of an ES.

Implementation- ‘Plan into Action’
There is a difference in accountability between those making policy (elected politicians) and those implementing it (state bureaucracies), which can lead to slippage between the intention of the policy and the actual way it is implemented (Newton et al, 2005). The causes of slippage can include: polices being changed due to economic pressure, bureaucratic procedures, avoidance of unseen side effects, modified to suit interests / agendas of the agencies implementing, or externally influenced by private organisations and pressure groups. Additionally agencies can be afforded discretion over how to implement a policy. In the case of London (due to the reduced control of LPA) policy delivery is reliant on the support it is given from partnerships between civil society, central and local government and the private sector (Keirstead et al, 2010). These collaborations form ‘energy partnerships’ that provide political leverage, funding and access to further collaborators. The Merton Rule is an example of this, where the implementation of this local policy encouraged the collaboration between stakeholders that provided “policy robustness” when it was challenged by central government (Keirstead et al, 2010). This provided an example of bottom up policy initiatives as the Merton Rule was adopted into the wider regional policy (TLP) in 2008.
Outputs and Outcomes - ‘Laws passed and money spent’ and ‘results or consequences of the outputs’
These definitions suggest that the policy results may not always be as intended. The Merton Rule is also an example of this, where the structure and desired outcome are perceived as straight-forward. The output being a number of policy compliant buildings receiving planning approval and the outcome being a 10% onsite CO_2 reduction. However, Keirstead et al (2010 p. 4875) argue there is still “uncertainty about the generated electricity output of these installations [versus planned]”. Analysis of TLP energy policy has shown that the evidence base is the ES document. However, much of the examined research has questioned the credibility of ES documents as to whether the predicted savings are actually being achieved in practice (Day et al, 2007 p.4; Day et al, 2009 p.2020; Keirstead et al, 2010 p. 4875; Rydin, 2010 p.253).
Evaluation and Feedback - ‘effects and conclusions drawn’
According to Keirstead et al (2010, p.4876) this stage is the most vital part of the cycle in order to feed the next policy iteration. In practice this area is often overlooked for several reasons: objectives are deliberately vague, policy agenda can change quickly, little funding available for evaluation, and evaluations are conducted internally rather than an independent body (Newton et al, 2005). It has been argued that the GLA analysis of the energy policy cannot be a credible evidence base for technology performance and saved CO_2 emissions in practice. The examined research would suggest that evaluation and feedback is currently not a part of the London energy policy cycle.

TLP energy policy cycle presented in table 2.7, has suggested that the final stage (*evaluation and feedback*), described as the most vital part of the cycle, is currently not being completed. The analysis of ES documents conducted by the GLA evaluates the outcome of the policy (i.e. number of policy compliant schemes, number of proposed HN-CHP and RE installations, and intended savings in CO_2). These outcomes are then being used to complete the cycle and create a feedback loop that is informing the next iteration of policy (figure

2.10). By excluding the final stage of the policy cycle, the unseen consequences of the policy are not being identified and the opportunity for independent knowledge gain is missed. The review by Rydin et al, (2007) of planning research suggests that when planners control the creation of knowledge, other stakeholders (e.g. local communities) can be disempowered and policy scrutiny is removed. The importance of knowledge gain to inform policy makers and stakeholders is discussed in the next section.

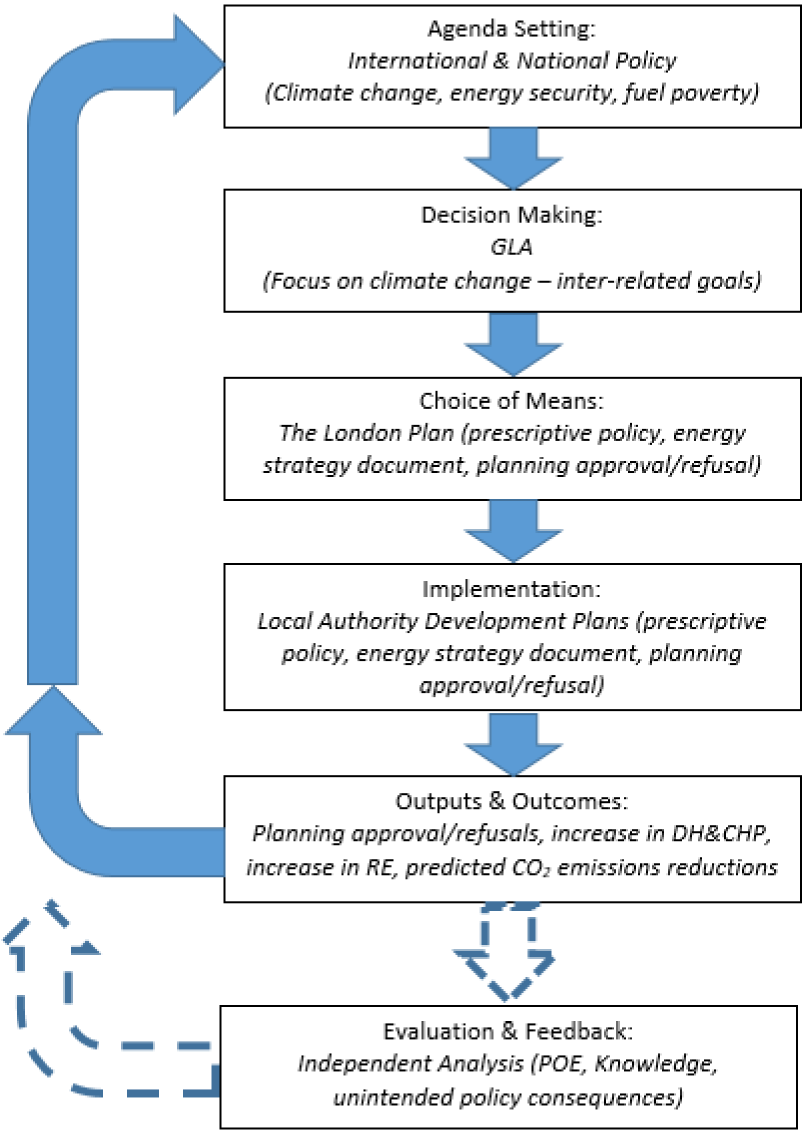


Figure 2.10: The Missing Stage of the Energy Policy Cycle in London (adapted from Newton et al, 2005)

2.5.2 Constructing Knowledge through Evaluation and Feedback

The evaluation and feedback stage of the public policy cycle identifies the importance of knowledge gain (Newton et al, 2005). The policy cycle also identifies the use of local planning control as one of the main mechanisms for LPAs to deliver national energy policy and CO_2

savings in new buildings. However, the mechanism is only one part, it is also a matter of the actors (i.e. planning officers) "will" to pursue the policy, and their knowledge of what it is, how to implement it, and to understand potential consequences (Rydin et al, 2007).

Rydin et al, (2007, p.366) argue *"if this knowledge is confined to the development industry, the planning system will be able to do little beyond accepting the industry's assurances that they are promoting sustainability"*. Considering the policy cycle without the evaluation and feedback stage, knowledge cannot be constructed. Therefore, in practice it would be the developer and local community that are unable to do anything beyond accepting the assurances of policy makers that current policy is delivering CO_2 savings.

Rydin's (2010) discussions of the role of technical society, considers how the balance of knowledge is being redrawn in the 'power relations' in planning control. The concept of evidence based policy is also discussed, which emphasizes the requirement of expertise among the relevant actors to inform knowledge. Feldman and March (1981, p.174) (cited by Mutshewa, 2010) observed within planning organisations that a lack of information will be cited as hindrance in many decision making processes, but often the information that is available was ignored. Research by Rydin et al, (2007) also challenges the view that planners have limited access to knowledge, the research points to a plethora of open websites and best practice guides. Instead the challenge is, how knowledge is "*constructed, recognised and embedded in relationships between actors"* (ibid p.366). The research considered the form of *'community of practice'* in enabling common pursuits such as generating dialogue, understanding and resultant learning between actors. In the case of London planning control the research suggested limited evidence of such practices occurring at the local level, identifying time pressures, rule bound nature of the work and departmentalism as inhibitors of this (ibid).

The research examined here recognises the importance of expertise within both LPAs and among stakeholders to facilitate the construction and sharing of knowledge, it has also suggested that there has been a lack of expertise within LPA departments. This is at a time where as a direct result of policy, complex engineering technologies (e.g. HN-CHP) are being placed directly within the remit of LPA (Rydin, 2010). The next section reviews the research literature relating to how technology is re-shaping planning energy policy.

2.5.3 Technology in Planning Policy

Rydin (2010) argues that technology has always been a part of urban planning (e.g. road building, air travel and nuclear power), but the nature of technological issues has changed with the prioritisation of climate change.

Instrumentalisation theory is the decontextualising of technologies into their useful properties (‘*Deworlding*’) so they can be reconstructed into new contexts to provide a potential new way of doing things and/or new world visions (‘*Disclosure*’) (Feenberg, 2003). While Freenberg developed Instrumentalisation theory to consider how technology and social change interact, Rydin (2010, p.245) applies the theory in a policy context – *“generating new policies around technologies can be seen as a form of disclosure in which policy discussions reframe the roles of technology within society and identify new possibilities”*. The Merton Rule (see section 2.2.1) is an example of forming policy on technology. The proliferation of the policy throughout LPAs led not only to the growth of RE infrastructure, but also economies of scale and cost reductions (ibid). However, the application of such theories have their issues within practice. Applying the rudimentary concept of a technology to fit another purpose potentially ignores the context of the technical detail and the specific context in which it is being applied. The deworlding of technologies in the formation of energy policy can remove the technical contact of the actors and stakeholders who must apply the policy to deliver a design and installation, and then maintain and operate the technology within the real world context. The ability of those actors to do this will ultimately determine the energy use and CO_2 associated with that technology (ibid). However, there is an opposing argument to this issue based again on the Merton Rule policy; on the one hand a blanket application of providing RE to every new development ignores the individual contextual factors specific to a building, development and site, that may result in a negative impact (e.g. socially, economically or technically). On the other hand this view could be considered *“to miss the point”*, that deworlding is necessary to envisage a *“vision of how change may occur”* rather than deliver real terms CO_2 reduction (Rydin, 2010 p.255). Thus, one could consider the purpose of energy policy as not to deliver CO_2 reductions but to simply put it on the agenda, providing the opportunity for reductions to occur.

The examination of deworlding and disclosure provides a new perspective to analysing how specific technologies are adopted into prescriptive policy and how these potentially end up being constructed as best practice without appropriate contextualising or evaluation.

2.6 Chapter Reflectance

This chapter has engaged with the relevant research to describe the top-down levels of planning policy framework that has placed some of the responsibility for energy efficiency and CO_2 reductions within the remit of local planning. The chapter has identified how planning was transformed from a perceived barrier, to a driver for RE installations. National policy statements and frameworks provided local planning authorities with the power to treat climate change as a material consideration of planning. It has also been identified that although there have been various national legislation designed to decentralise the responsibility of planning, LPA do not have complete autonomy in producing their local plans, they are required to conform to the national and regional guidance. It has been shown that various national policy guidance and government white papers have placed HN and CHP at the forefront of decarbonising heat in buildings. LPAs have been directed to deliver local policy that positively promotes HN and CHP and develop opportunities for community energy infrastructure.

The chapter has also identified successive bottom-up policies such as the *Merton Rule* and the Mayor of London's *energy hierarchy*. The GLA's own analysis of the policy has indicated that they are successful in delivering the policy aims. The ES has been identified as the critical document for demonstrating compliance with policy and evaluating the outcomes. The review of available research has identified that the ES document is being used as a form of evidence to demonstrate real term CO_2 reductions and consequently a demonstration of 'successful' policy. However, there remains a considerable level of doubt regarding the reductions in CO_2 that have been achieved in practice. Where the expertise and knowledge for evaluating the policy and design proposals lies, has also been identified as potential conflict in the power relations between LPA and developers. The critical need for empirical research has been identified to provide: independent evaluation of policy, feedback to policy makers of the potential successes and unintended consequences, and to aid the generation of knowledge among the various stakeholders.

CHAPTER 3: THE APPLICATION OF HEAT NETWORKS AND CHP IN RESIDENTIAL BUILDINGS

This chapter focuses on the technologies of HNs and CHP. Given that the focus of this research is on the policy that promotes these technologies and their performance in practice, it is important to understand how they work, the key components, and their historical use in buildings. The section will also discuss the principles of how these technologies are expected to reduce CO_2 in buildings. Chapter 2 focused on national and local policy that promotes these technologies and requires developers to apply them 'where feasible'. This chapter will examine the available research and design guidance to identify what would be considered a feasible development and what are the most appropriate feasibility assessment methods.

3.1 Heat Networks

A HN is the distribution of thermal energy from a centralised generation source to multiple end heat consumers. In a HN, thermal energy is generated separately to the location of the consumer (either in the same or different building) and the thermal energy is distributed via a medium (typically hot water in pipes) to an end heat consumer (e.g. building or individual dwelling). There are many terms used to describe the distribution of thermal energy from a decentralised source (e.g. decentralised energy, distributed energy, district heat networks, community heating, and communal heating). The main difference between these terms is the scale at which the thermal energy is being distributed (GLA, 2013a):

- *Community/Communal Heating Network (Small Scale): single development or building*
- *District Heat Networks (Medium Scale): multi-development*
- *Decentralised Energy (Large Scale): area-wide*

In this research, where local level planning policy is the focus, small scale HNs are the appropriate technological focus. Medium and large-scale are not an appropriate as they have far reaching impacts on an urban planning and development system. The planning, design and construction of medium and large-scale HNs can require the involvement of multiple local councils, planning authorities, developer organisations, government agencies (e.g. Transport for London), and commercial consumers. Only a small-scale HN consisting of a single development, a single developer and single LA will allow rich and manageable analysis of the research content.

There are key components that make up a HN. These are described below and in figure 3.1:

- Heat Generation Sources – These can include conventional gas boilers, CHP and other LZC technology (e.g. biomass, geothermal, solar thermal, heat pumps, waste heat, and heat from waste). The generating technologies are typically located together in an energy centre (also known as plant room or boiler house).
- Pumps – Pumps circulate the hot water around the distribution network. Pumps are located in energy centre.
- Distribution pipework – carry the hot water from the energy centre to the heat consumers. Pipes are insulated to minimise heat loss in distribution. Pipes can be installed below ground to connect multiple buildings and above ground throughout buildings in service risers.
- Heat Interface Units (HIU) – HIU provide hydraulic separation and control between the distribution network and individual heat consumer. They also may contain a heat meter for monitoring thermal energy consumption. A HIU can be at a building level at the entry to the building (also known as a building 'heat substation') and at individual dwellings.

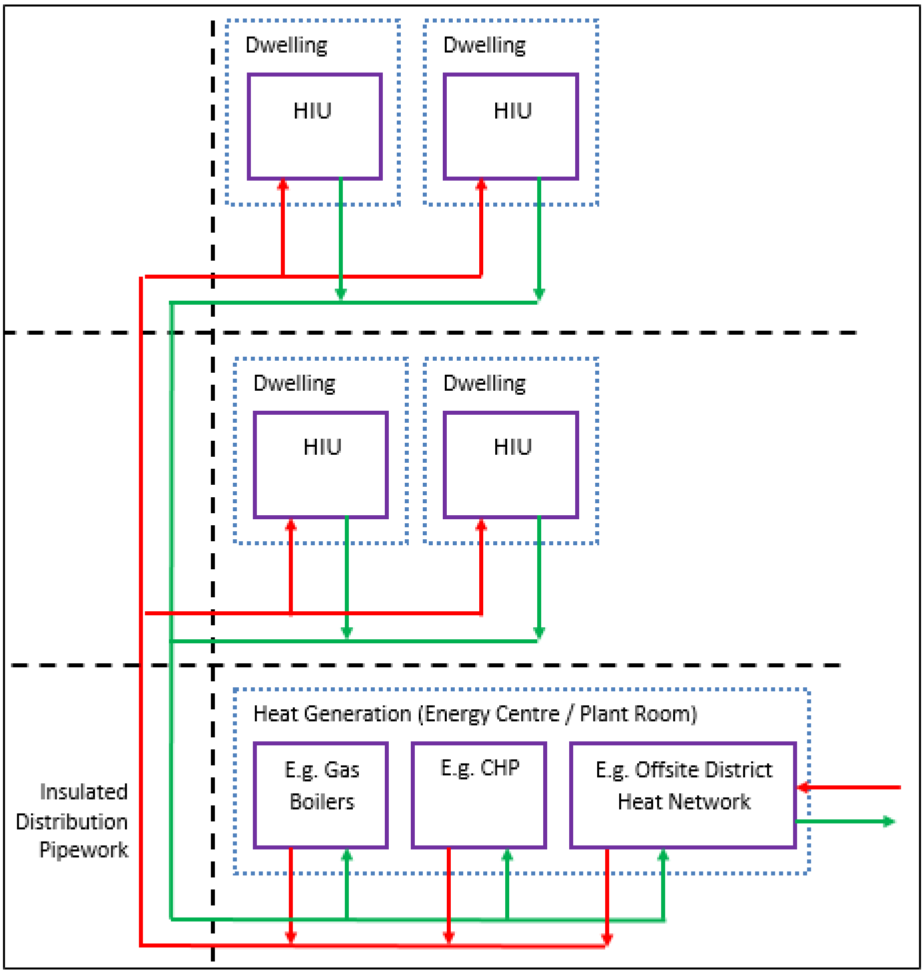


Figure 3.1: Key Components of a Small-Scale Heat Network (author, 2019)

3.2 A Brief History of Heat Networks in the UK

Contrary to the consistent development of large-scale heat networks in many European countries, development in the UK has been a start stop process with only a few niche schemes being developed (Russell, 2010). Many of the large-scale heat networks in central and eastern Europe are the legacy of a communist era, where central control and ownership of infrastructure and energy services meant HN could provide subsidised energy to much of the population and act as a tool in promoting political ideologies (Poputoaia & Bouzarovski, 2010). In the UK the absence of substantial support from government and lack of coordination with energy suppliers meant that there was no long-term stability or economic objectives to offset the unattractive short-term economics of HNs.

In 2008, the proportion of homes connected to HNs in the UK was 2%, compared to 98% individual heating systems. Apartments make up the predominant proportion (89%) of dwellings connected to HN in 2008 (EST, 2008).

The Heat Metering and Billing Regulations (2015) required all owners/suppliers of a HN to notify the Secretary of State of the network existence by 31st December 2015. The current data released under the regulation has identified 17,125 HN in the UK, with circa 446,517 dwellings connected (BEIS, 2018).

3.3 Combined Heat and Power

The UK's conventional energy supply system is the separate production of electricity (from power stations) and heat (from boilers). CHP is the production of both heat and electrical power in a single process (CIBSE, 2013). In a conventional power station the majority of thermal energy created is rejected. Whereas CHP with the waste heat is captured and used for heating buildings or for industrial processes, saving approximately 23-30% in primary energy (ibid). Figure 3.2 is a simplistic representation of the commonly used 'energy flow diagram' of CHP versus conventional energy generation. The Skankey diagram demonstrates how a CHP can achieve the same energy output as conventional energy generation with less primary energy input (no energy units are given in the example).

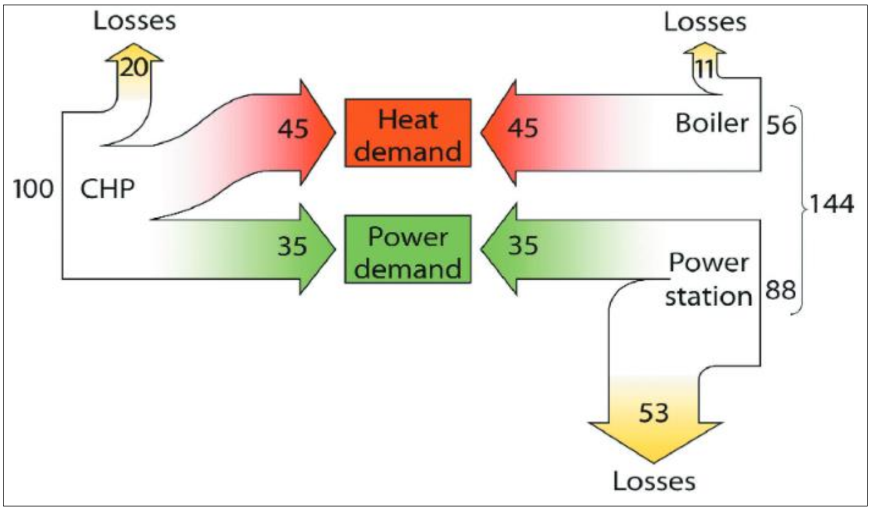


Figure 3.2: Simple Energy Flow Diagram of a CHP versus Conventional Systems (Carbon Trust, 2004)

3.4 A Brief History of CHP in the UK

In the UK CHP has been used since the nineteenth century and traditionally used in industrial applications (Russell, 2010). The oil crisis in the nineteen seventies dramatically increased fuel costs and raised fears over security of supplies, leading to a drive for industry to reduce fossil-fuel consumption. Despite this CHP capacity declined between the nineteen-fifties to eighties as industrial processes changed to lower demands for heat compared to power. CHP technological advancement allowing lower heat to power ratios saw a resurgence along with support from government that set-up public bodies to promote industrial CHP. The late eighties saw a turning point, with growth established in installed capacity and electricity generated (Russell, 2010; Brown & Minett, 1996).

Compared to the long historical use of CHP in large-scale European HNs, the UK had limited experience of this practice. A study carried out on behalf of the Department of Trade and Industry (dti) estimated that in 1980 the UK's potential of small-sale CHP was 300MWe (Russell, 2010). A series of subsequent demonstration projects proved successful, although several areas for improvement were identified (ibid):

- More accurate feasibility assessment, design and specification
- Plant and component performance
- Component reliability
- Coordination of maintenance support

These and other projects helped to transform the small-scale CHP industry, leading to considerable improvements. The second-generation of small-scale 'packaged' CHP's (<500 kWe) have formed the basis for their application in buildings (ibid).

The UK Government introduced a voluntary scheme to monitor, assess and improve the quality of CHP in the UK. The CHP 'Quality Assurance Programme' (CHPQA) was introduced in the year 2000 and assesses schemes on the basis of their energy efficiency and environmental performance. Accreditation to the CHPQA scheme allows the owner to apply for a range of fiscal benefits including, renewable obligation certificates and climate change levy exemption. Numbers and capacities of CHPQA registered schemes are available and presented in the annual Digest of UK Energy Statistics (DUKES). Figure 3.3 shows that the number of installations and capacity has increased since 1995 (this does not include micro-CHPs). The total capacity can be seen to increase and decrease overtime, whereas the overall number of schemes generally increased. These fluctuations in capacity can be attributed to individual large scale (>2MWe) schemes being decommissioned or installed. The statistics show that the number of CHPQA schemes increased by 50% between 2010 and 2016. Notably the same time as the change to TLP energy hierarchy that prioritised CHP (GLA, 2011a) (see section 2.2).

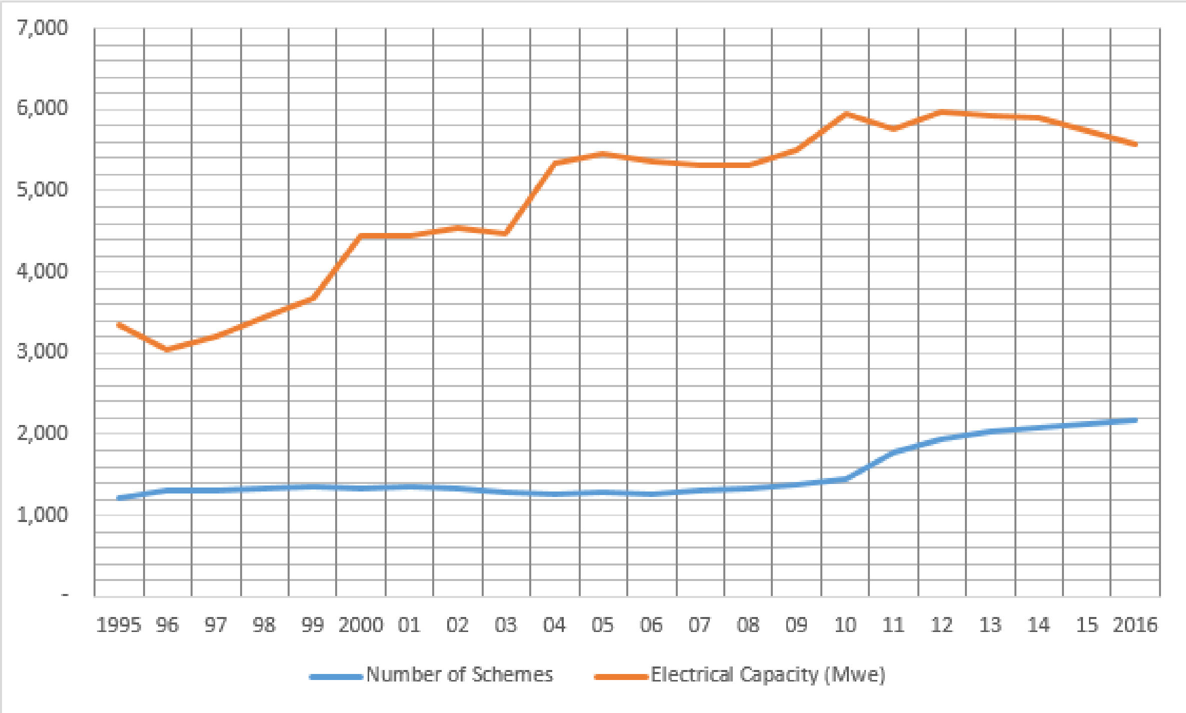


Figure 3.3: Increase in Number and Capacity of CHPQA schemes in the UK since 1995 (adapted from BEIS, 2017)

3.5 Reducing CO_2 Emissions from Buildings

The considered political benefits of HN-CHP have been discussed in the energy policy examination in chapter 2, further detailed technological and economic considerations are provided here.

It is often common to characterize the policy challenge surrounding energy as a 'triangle' of concerns relating to economy, environment and security (McGowen et al, 1993). The Chartered Institute of Building Services Engineers (CIBSE) describes these challenges (CIBSE, 2013):

- Climate Change - energy systems must reduce CO_2 to combat climate change.
- Security of Supply – the UK's indigenous energy resources (coal, oil and natural gas) are in decline and the UK will be increasing more reliant on imported fossil fuels. The efficient use of energy resources is therefore required to limit these uncertainties.
- Energy Prices - investment to replace ageing infrastructure and the development of low carbon energy strategies will increase the cost of energy supply. The third challenge is to maintain competitive energy prices to enable industry and society to thrive.

CHP has been recognised as a technology that can help meet all three of the energy challenges (CIBSE, 2013). Figure 3.2 demonstrated how CHP uses less primary fuel to produce the same amount of electrical and thermal energy as conventional methods, thus reducing fuel consumption and resultant CO_2.

Bonham-Carter and Woods (2006) suggest that the greatest potential for utilising the heat output from CHP is to supply a HN. HN's with a mix of heat consumers and demand patterns can complement each other. Although CHP can also be used in industrial applications and single domestic homes (mirco-CHP), this research only considers the use of CHP as part of a small-scale HN (HN-CHP).

HNs have also been recognised as a key technology to meet the energy challenges. A HN is considered to improve the energy performance of heating systems by utilising larger capacity plant at greater thermal efficiencies than can be achieved by smaller individual systems (CIBSE, 2015). They are also able to provide security of supply and system resilience by utilising multiple heat sources with fuel flexibility. The Energy Saving Trust (EST, 2005) lists further benefits including: reductions in energy costs; reduced operational costs (e.g. operating maintenance, plant replacement, and administration); incorporation of cost efficient technologies (e.g. CHP); and they create potential revenue streams via the export of excess energy. 'Future proofing' buildings through the installation of HNs makes it relatively easy to connect to a large-scale district heating scheme in future or to change the energy source (Bonham-Carter et al, 2006).

3.6 Feasibility Assessment of Heat Networks and CHP

This section examines what are the suitable applications and assessment methods for small-scale HNs and CHP. The purpose is to understand the key technical and economic considerations and assessments that designers should undertake when they apply TLP energy policy.

3.6.1 Heat Density

The policy guidance documents examined in section 2.4, refer to the term 'heat density'. Heat density (HD) is the annual requirement for heat (kWh) in a specified area (m^2). The London Heat Map (see figure 2.1) uses annual heating fuel usage to identify areas of high HD (kWh/m^2 /year) and therefore where a HN may be viable. Heat power density (also known as heat load) is the power (kW) requirement within a specified area (m^2). Although seasonal variations will change the level of HD, feasibility assessments use the average annual HD (the impact of seasonal variation on the case study HD is examined in Chapter 7). HD is important for the feasibility of HNs as lower density increases distribution pipe length and diameters. The examined industry and academic literature related to HN and CHP, state the necessity for a 'high-heat density' and provide examples of development types: mixed-use (commercial and residential); high-rise (>15 stories) or high density (50 dwellings per hectare) residential developments (DECC, 2009; 2009a; Kelly & Pollitt, 2010; Evans, 1993; EST, 2005; Zinko et al, 2008; NHBC, 2009). HD is fundamental to viability and is independent of the technology supplying heat (Foster, Love, Walker & Crane, 2016). HD is a primary measure used in mapping the potential for HN in the UK and London (Grainger, 2016; GLA, 2011c). HD can be calculated by equation 1.

Equation 1: Heat Density (HD)

Heat Density (kWh/m^2.year) = Annual Energy Demand (kWh/year) / Area (m^2)

Where:
Annual Energy Demand (kWh/year) = sum of all thermal loads (i.e. domestic SH and DWH)
Area = site area (m^2)

Meanwhile, national and regional planning policies as those discussed in chapter 2, have resulted in modern buildings being designed to significantly reduce heating demands through energy efficiency measures.

Figure 3.4 illustrates the reduction in predicted heating demand for typical new residential dwellings designed to different levels of energy efficiency (Code for Sustainable Homes[9] level 4, 5 and 6). As the thermal energy efficiency of building fabric increases lowering space heating demand, hot water is expected to overtake as the dominant heat load in buildings (EST, 2008 p.10).

[9] CfSH – a national standard to improve overall sustainability of new homes (discontinued in March 2014). The 'Code' set a single framework for the measurement of sustainable credentials, including energy efficiency.

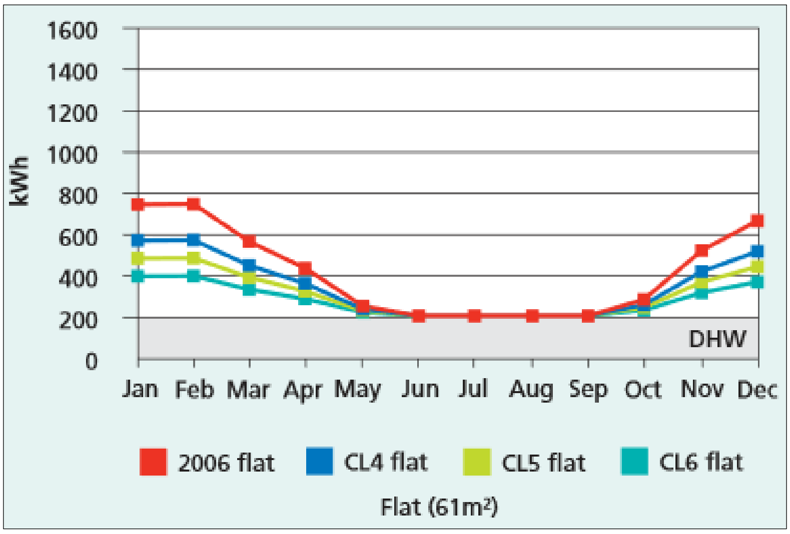


Figure 3.4: Estimated Monthly Heat Demand of a Flat Built to Varying Levels of Energy Efficiency (EST, 2008 p.9)

Linked to HD is the '*linear (or line) heat density'* (LHD) of the distribution network. The LHD is the heat demand served per meter length of distribution pipework, expressed in kWh/m. LHD is calculated by dividing the annual heat demand (kWh) by the length of distribution pipework serving that demand (equation 2). The LHD will affect the capital costs (pipe length/diameter) and operational cost (heat losses) of the distribution network. A survey of annual heat distribution losses (%) as a function of line (linear) heat density (MWh/annum/meter) for European HNs demonstrates the significant increase in measured heat losses related to LHD (figure 3.5). However, it should be noted that heat losses can be found to vary by a factor of three for the same heat density, suggesting other influences are related to heat losses (Nussbaumer and Koppejan, no date), including:

- Pipe diameter
- Operational Temperatures
- Insulation Thickness (and thermal performance)
- Operational Hours

Equation 2: Linear Heat Density (LHD)

$$LHD = \frac{Edel}{HNpl}$$

Where:
LHD – Line Heat Density *(MWh/m/year)*
E_{del} – Energy delivered to the consumers
HN_{pl} – Heat Network Pipe Length (m)

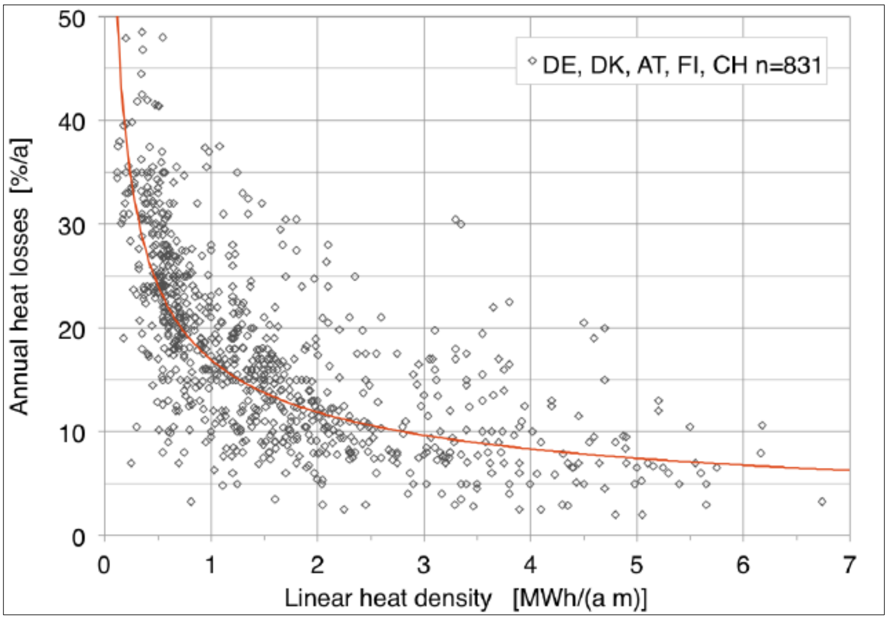


Figure 3.5: Survey of European Heat Networks – Heat Distribution Losses as a Function of Linear Heat Density (MWh/annum/meter) (Nussbaumer & Thalmann, 2014 p.18 fig.8)

The majority of the examined academic literature relates to large-scale district wide HNs, only a small proportion relate to small-scale. The analysis of small-scale HN are presented within a context of inter-connected buildings of multiple-usage (i.e. residential, commercial, hospitals, leisure, etc) or minimum heat densities (Finney et al, 2013; Fragaki, Andersen, & Toke, 2008; Hawkey et al, 2013; Evans, 1993). Difficulties of residential only HN are discussed in works by Hawkey et al (2013) and Brand et al, (2014) that cite the homogenous load profile; low summer domestic hot water loads; and insufficient network cooling as technical and economic limitations to HNs at this scale.

A review of the academic research and secondary industry guidance provide an estimate of minimum HD and LHD at which a HN is viable (table 3.1). Research by Zinko et al (2008) and Rosa and Christensen (2011) analysed the economic feasibility of ultra-low HD networks (<0.3 MWh/m/yr and <0.2 MWh/m/yr), however, these studies were based on theoretical models and consider heat losses from underground pipework only. These studies do not consider distribution pipework within a building, which can have higher distribution losses than pre-insulated underground pipework (CIBSE, 2015, p.43). Furthermore, the Zinko et al (2008) study increased HD by allowing additional loads from hot water appliances that would now typically be powered by electricity (e.g. washing machines, dishwashers and tumble dryers). Yang and Svendsen (2018) found that a HN in ultra-low density areas had heat distribution efficiency ranging from only 45% to 75%. Their study showed that efficiency increased in the winter months in line with increased HD.

The GLA conducted a study into DE capacity in London (GLA, 2011c), where the viability of different levels of HD were considered. Their research of the existing literature found that the technical viability of HN to be above 10kWh/m^2/yr, however, this was only considered viable when certain prerequisites were available. London was found not to include these prerequisites and their study concluded that a HD of 50kWh/m2/yr would represent a more practical minimum HD for the establishment of HNs (GLA, 2011c p.104). This HD was also used by Grainger (2016 p.10) in his spatial heat analysis of the UK. In comparison to the guidance from European Commission (threshold 130kWh/m^2/yr) the HD used in the UK and London could be considered to be low density (European Commission, 2018 p.8).

Table 3.1: Minimum Heat Density and Linear Heat Density for Heat Networks

Document	Minimum Heat Density	Minimum Linear Heat Density
Decentralised Energy Capacity Study – Phase 1: Technical Assessment (GLA, 2011c)	50kWh/m^2	-
European Commission's guidance note on Article 14 of Directive 2012/27 (European Commission, 2018)	130 kWh/m^2	2.5 MWh/m
Heat and Energy Saving Strategy (DECC, 2009a)	3 MW/km^2	-
Community Energy: Planning, Development and Delivery 2012 (King et al 2012)	3 MW/km^2	-
Status Report on District Heating Systems IEA Countries (Nussbaumer et al, 2014)	-	1.8 MWh/m/yr
Analysis of the UK potential for Combined Heat and Power (DEFRA, 2007)	3 MW/km^2	-
District heating (DH) network design and operation toward a system-wide methodology for optimizing renewable energy solutions (SMORES) in Canada: a case study (Dalla et al, 2012).	-	1.5 mWh/m/yr
Energy Distribution: District Heating and Cooling – DHC (UP-RES, no date)	-	2 MWh/m/yr
Cost Benefit Analysis of the potential for high-efficiency cogeneration and efficient district heating and cooling in Ireland (seai, 2015)	-	3 MWh/m/yr
CHP Systems for blocks of flats? A financial assessment (Dupe et al, 1994)	20 MW/km^2	-
District Heating Distribution in areas with low heat demand density (Zinko et al, 2008)	10 kWh/m^2	0.3 MWh/m/yr
Heat Pumps in District Heating (Foster et al, 2016)	125 kWh/m^2	-
The Role of District Heating in Achieving Sustainable Cities: Comparative Analysis of Different Heat Scenarios for Geneva (Quiquerez et al, 2016)	25-50 kWh/m^2	-

3.6.2 Heat Network Energy Losses

The efficiency of the HN distribution is defined by the heat generated plus auxiliary energy (i.e. pumps) used versus the useful heat delivered to the end consumer. Much of the current research and guidance considers how to minimise losses in:

- Distribution heat losses (DHL), and
- Auxiliary energy (AE)

As the water within the distribution network is above the surrounding ambient temperature there is a thermodynamic process of heat loss from the pipework. Thermal insulation is used as a method of minimising the heat loss. The overall length of distribution pipework (including control valves) from the heat generation to the consumer (e.g. dwelling) will determine the overall loss from the distribution network and should be calculated in the feasibility assessment (CIBSE, 2015). Below ground pipework is typically manufactured pre-insulated, whereas above ground pipework is typically insulated by the plumbing contractor onsite. Issues with poor installation of insulation have led to significant heat losses and lower system efficiencies (Blackwell, 2013).

Recent works are examining the methodology and benefit of having lower flow temperatures (<90^{o}C) and maximising the dT (i.e. lowest return temperature possible). Low return temperatures reduce peak volume flow rates, require smaller pipe diameters, and thus reduce heat losses and pumping costs (CIBSE, 2013; CIBSE 2015; Zinko et al, 2008; Blackwell, 2013; EUDP, 2014; Xing et al, 2012). Research by Olsen et al (2008) analysed the heat losses on a ultra-low temperature HN for low energy houses (Flow: 50^{o}C, Return: 22^{o}C) and found heat losses within the region of 10-14% of the HN heat consumption; furthermore, they acknowledge that practical experience shows that real heat loss will be 20-30% higher.

The total peak mass flow of water (l/s) and total network pressure resistance (kPa) determines the capacity of the distribution pumps. Pump energy consumption has not been widely reported. Available data from the Danish District Heating Association measure electrical usage of 0.2%-1.5% of heat demand for smaller schemes (figure 3.6) (Woods & Zdaniuk, 2011). Industry guides suggest a design maximum pump energy of 1% of the total heat energy delivered to the HN (CIBSE, 2015).

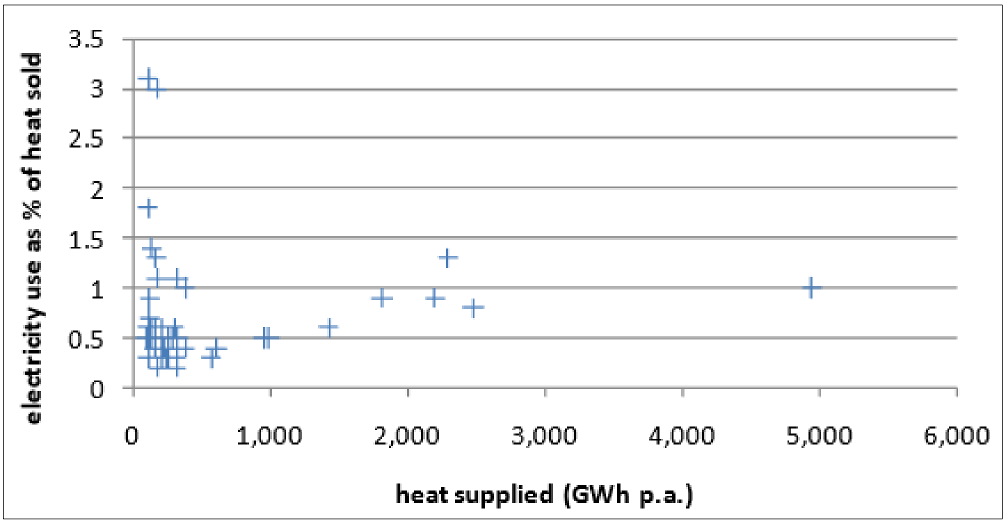


Figure 3.6: Electricity Used in Danish Heat Networks (Wood et al, 2011)

There is no equivocal maximum AE usage or DHL performance standard defined within UK building regulations, industry design standards or academic literature. Guidance by the professional institute CIBSE (2015, p.38) states that a maximum heat losses (kWh) must be less than 15% of the total consumed energy demand (kWh). This appears ambitious given academic studies that show heat losses to regularly exceed 15%. For example, in Denmark heat losses are report as 16%, and rise to 21% when the largest scale HN are not included (Rosa et al, 2011). In Sweden the heat losses are approximately 12% (Vesterlund et al, 2013). There is a growing body of research analysing low density HN developments, although they are mainly theoretical, they still predict heat losses between 17%-20% (EUDP, 2014; Rosa et al, 2011; Zinko et al, 2008)

The review has shown that HNs energy inputs (DHL and AE) should be included within a feasibility analysis (CIBSE, 2013; 2015; Xing et al, 2012). This should include the initial planning of pipework distribution route, designed average dT, pipework size and thickness of insulation (CIBSE, 2015, p. 24).

3.6.3 Modelling Heat Demand

The heat demand of a development is a major technical and economical factor for the feasibility of a HN and CHP. An estimate of both the peak heat demand (MW) and annual heat consumption (MWh/year) is considered the first step in a feasibility assessment (CIBSE, 2015). While existing buildings can utilise historical consumption records, calculating the energy use in new developments is reliant on computer models and therefore difficult to estimate with accuracy (ibid).

There are many research papers discussing the accuracy of computer models to predict building energy use and occupant behavior (see Bordass et al, 2004; De Wilde, 2014; Menezes et al, 2012). These research studies conclude the primary causes of inaccuracy in computer models are: the type of modelling software used (simple or dynamic); the assumption made (e.g. occupancy levels); and the accuracy of the input data (e.g. efficiency of systems, performance of building fabric, local weather data). The EPG related to computer modelling is discussed in greater detail in chapter 4. The focus of this section is to discuss the required outputs of the models to evaluate the feasibility of HN and CHP rather than the modelling process.

With the installation of heat meters (HM) in modern HN, real time data is starting to be collected and analysed to show peak consumption. Figure 3.7 demonstrates the analysis of '*Guru Systems*' (a heat metering provider) and their estimation of heat capacity required per dwelling. The demand curve is based on half-hourly meter readings of 1000 domestic customers. As can be seen there is an estimated reduction in diversified load compared to the commonly applied Danish Standard (DS 439:2009) (CIBSE, 2015). Guru (2018) have also used the data to estimate that lower demand loads occur more frequently than the higher loads. This is important for the feasibility of modern HN as network pipe sizes are based on the peak heat loads. The size of pipe will have a consequence on the DHL, AE, capital and operational costs.

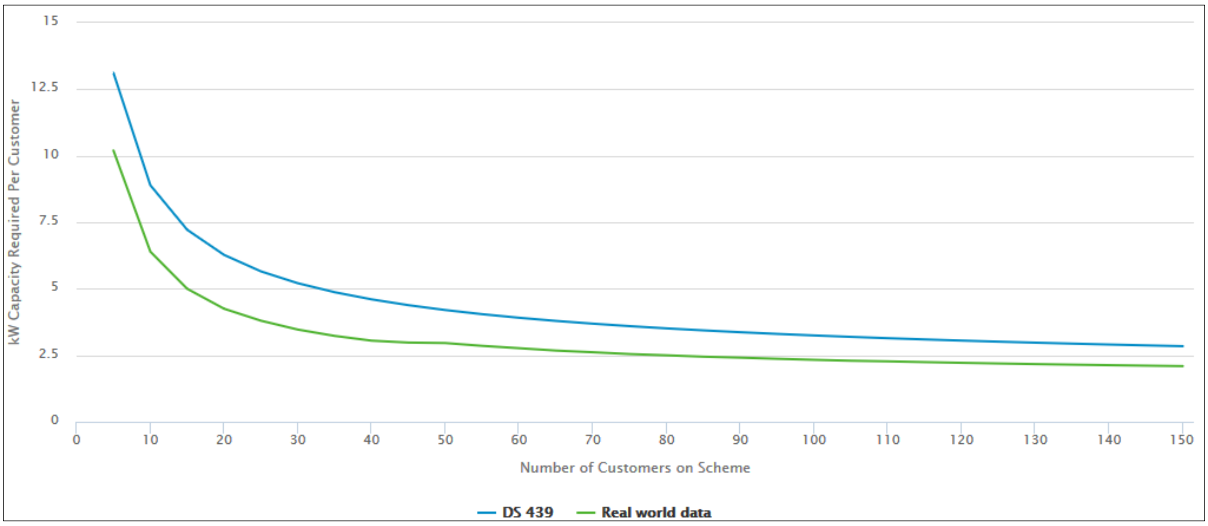


Figure 3.7: Heat Network Domestic Customer Heat Load Diversity (Guru, 2018)

For new developments annual heat demands are calculated by computer models (simple or dynamic) based on building fabric performance (for space heating) and occupancy levels (hot water). CIBSE (2015) design guidance state that a monthly profile (based on degree-days methodology) and a 24-hour variation in demand should be created (figure 3.8). The annual heat demand can be used to calculate LHD and used to compare different heat generating technologies.

Chapter 2 examined the policy guidance for creating an ES and calculating the energy demand and CO_2. The policy guidance states that these should be calculated using SAP assessments (GLA, 2016). The SAP method will calculate the monthly and annual space heating and hot water demands (kWh) of a single dwelling. The SAP calculates the energy demand (kWh) and resultant CO_2 ($kgCO_2$) of the thermal systems including any attributed reductions in CO_2. The SAP assessment method is discussed in more detail in chapter 4 and 7, here the SAP guidance relating to heat demand is reviewed.

The SAP guidance document (BRE, 2012) describes the user inputs and the calculation methods used to calculated the energy and CO_2 from each heat source (e.g. gas boilers and CHP) and the overall HN including losses (DHL and AE). The assessor must enter fuel type (e.g. gas, electrical, biofuel) and thermal efficiency (%) of the different heat sources, if figures are not known, default are provided. The proportion of heat covered by each heat source, known as the 'heat fraction', must be calculated. The sum of all heat fractions must equal 1. CIBSE guidance (2015, p.74) states that when using SAP calculations for a HN, the heat fraction of each plant should be based on design calculations.

For HN energy losses the SAP 2012 applies a default figure for AE of 1% of calculated heat energy requirement (BRE, 2012, p.49). For DHL a factor is applied to the calculated heat energy requirement, known as the 'Distribution Loss Factor' (DLF). Default values for DLF are given related to type and age of system, these default values equate to a distribution loss of between 5-20%. Where criteria 1 or 2 cannot be met or the LHD is below 2MWh/m/year, the HN designer must calculate the DLF (BRE, 2012 p.49) (equation 3).

SAP 2012 DLF Default Criteria:

1. *The only dwellings connected to any part of the network are flats, or*
2. *The total trench length of the network is no longer than 100 metres, or*
3. *The linear heat density is not less than 2 MWh/year per metre of network.*

Equation 3: Distribution Loss Factor (DLF)

$$DLF = \frac{Egen}{Edel}$$

Where:
DLF – Distribution Loss Factor
E_{gen} – Total Heat Generated (kWh/year)
E_{del} – Total Heat Delivered (kWh/year)

The review of the academic literature and industry guidance is clear that accurate assessment of peak and annual demand loads are essential to the feasibility of a HN and CHP. There is available guidance on how these demands can be calculated by using formulas or computer calculation models. It has also been identified how real data is starting to demonstrate that heat demand loads are below those estimated. What has also been discovered in the examination of the SAP, the underpinning calculation methodology for energy policy, is that default values for heat losses (5-20%) and pumping (1%) energy are at the low-end of available real world data (figure 3.5 and 4.6).

3.6.4 Feasibility of CHP for Residential Buildings

CHP has been promoted as the primary technology to be used with HN that will provide the CO_2 savings needed to meet the climate change energy policy and provide the long-term revenues to recover capital investments (Catto, 2008; Hawkey, 2012; McManus, Gaterell, & Coates, 2010). Although more expensive and less electrically efficient per MW than centralised electricity plants, the ability to utilise the heat generation through local HNs dramatically increases the efficiency of the process (Fragaki et al, 2011). The literature argues that a detailed feasibility study must be completed to ensure that a CHP is an economically viable technology (Dupe et al, 1994; Carbon Trust, 2004; BESA, 2017; CIBSE, 213; Kelly et al, 2010; ade, no date.)

Kelly et al, (2010) describes three methods of designing a CHP based on a development's heat or electrical demand:

Summer (Base) heat load – the CHP heat will meet the summer load with the winter heat load being met with additional heat generation technologies. This is the most common and current design method suggest by UK energy policy (GLA, 2011; 2016). This however, limits the electricity output capacity of the CHP and thus potential revenue stream through electricity sold to the electricity grid.

Winter (Peak) heat load – the majority of the developments heat load is provided via the CHP, with the increased electrical output being used onsite or sold. However, the heat capacity is under-used in the summer with either heat being dumped (lowering the energy efficiency and CO_2 reduction) or CHP running at part load with lower operational efficiencies. The opportunity to store heat onsite is limited due to the low summer demands.

Electrical Load – revenue is maximised by tailoring output to peak electrical power demands. As power and thermal demands may not be simultaneous, thermal stores are used to store generated excess heat until needed. Additional heat generation technology may be required to meet the peak thermal loads.

The examined research suggests that heat output should be the main focus when designing CHP to meet energy efficiency targets, consistent with the need to utilise generated heat to improve efficiency (Finney et al, 2012; Fragaki et al, 2008a; 2011; Laajalehto et al, 2014; Rezaie et al, 2012). When sizing on heat demand, a common CHP proportion is 60%-80%, with the remaining demand being met from a secondary heat source (CIBSE, 2015; Woods et al, 2011, p.15). A further common figure provided when considering the feasibility of a CHP is run hours, with 14-17hrs/day or 4000-5500hrs/year stated as the minimum for a CHP to be economical (Carter & Woods, 2006; BESA, 2017; Carbon Trust, 2004; Evans, 1993). The Carbon Trust, suggests a minimum of 5,000 hours and that heat and power loads should be simultaneous. Therefore, a daily load profile (figure 3.8) for heat and power is essential for establishing the feasibility of a CHP (Dupe et al, 1994; Carbon Trust, 2004; CIBSE, 2013; ade, no date). The Carbon Trust (2004) advises that the capital investment of a CHP may be substantial to a project and that the capacity should be matched to a buildings base heat and power loads. Furthermore, a range of capacities should be included in any feasibility study to ensure economic efficiency has been maximised.

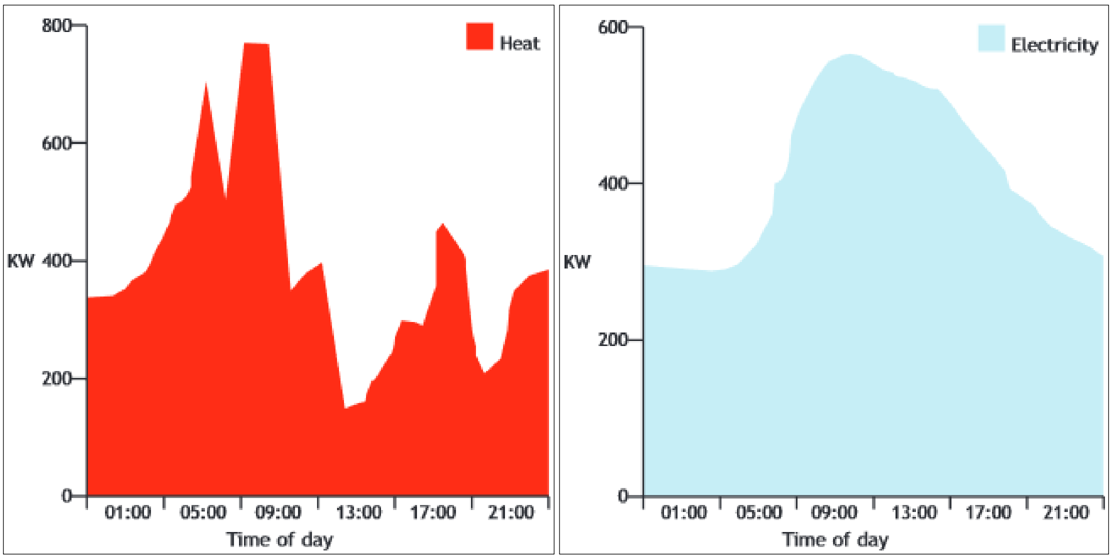


Figure 3.8: Example of Daily Heat and Power Load Profile (Carbon Trust, 2004 p.19)

To complete a feasibility assessment of a CHP for a HN the guidance advises that following needs to be considered:

- Capital Costs – although the capital and installation costs of CHP are significantly higher than for conventional boiler plant, a CHP can yield monetary savings in operational costs and, if sized correctly, can provide a return on investment. Figure

3.9 provides an estimate of installed costs of CHP based on electrical capacity (kWe). (CIBSE, 2013; BESA, 2017)

- Fuel Costs – the current and future prices of gas and electricity are critical to the long term economics of a CHP. The costs for gas (p/kWh), electricity import (p/kWh) and potential revenue from electricity export (p/kWh) should be investigated.
- Maintenance Costs – a CHP will need to be maintained regularly to minimise downtimes and ensure economic outcomes. Figure 3.9 provides estimates of maintenance costs based on CHP electrical capacity (kWe).

There are a range of CHP assessment tools to calculate reduction in CO_2 and simple payback (see Carbon Trust, 2004; DECC, 2013). Detailed evaluation of a CHP would require the consideration of full economic terms, such as Net Present Value and Internal Rate of Return. However, Dupe et al (1994) suggests that for planning stage feasibility a simple payback method is suitable to determine the economic feasibility for CHP. Table 3.2 presents a simple payback template from the Carbon Trust (2004) that can be used to compare the simple payback of a range of CHP capacities.

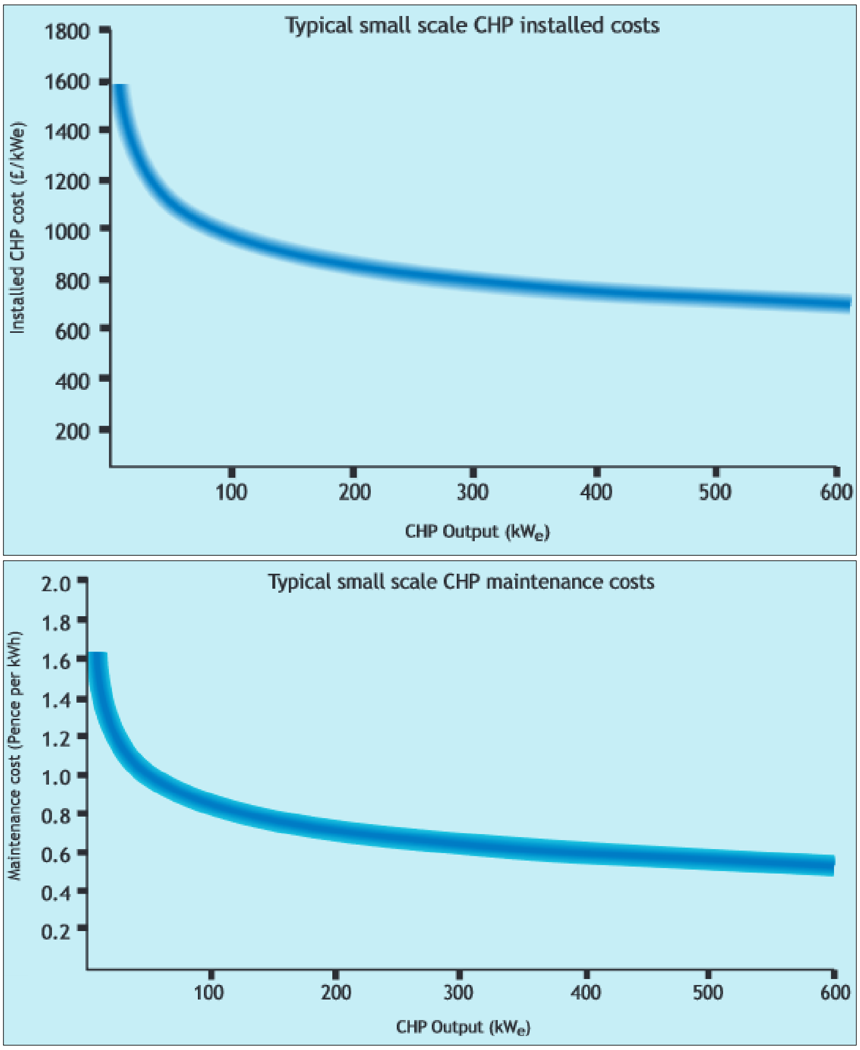


Figure 3.9: Estimate of CHP Installation and Maintenance Costs Related to Electrical Capacity (Carbon Trust, 2004 p.23 & 24)

Table 3.2: Simple Payback Period Analysis for CHP (adapted from Carbon Trust, 2004)

CHP Size	**-**	**Value**
CHP Thermal Output	kWth	
CHP Electrical Output	kWe	
CHP Fuel Input	kW	
Energy Cost Savings		
CHP Run Hours	Hours	
Heat Utilisation	%	-
Heat Supplied	MWh/yr	-
Displaced Thermal Fuel Savings	£/yr	A
Displaced Electricity Import	MWh/yr	-
Displaced Electricity Import Savings	£/yr	B
Total CHP Savings	£/yr	C = A+B
Operational Costs		
CHP Fuel Input	MWh/yr	
CHP Fuel Input Costs	£/yr	D
Maintenance Costs	£/yr	E
Total Operating Costs	£/y	F = D+E
Financial Return		
Net Savings	£/yr	G = C-F
Capital Costs	£	H
Simple Payback	**Years**	**I = H / G**

Consistent with the examined research, Rezaie et al, (2012) review of the potential of CHP prioritised heat as the primary requirement and focus of the review. The study provided little consideration of matching the electricity demand and generation, *"electricity can be used onsite or sold to the local electricity utility"* (ibid, p.5). However, creating revenue from CHP especially small scale is difficult within the current liberalised electricity market. The Carbon Trust (2004) identified that where designers have ignored the electricity demand in the sizing of a CHP, they have inadvertently ended up exporting power and not getting any revenue from the export. Crane (2018) argues that a CHP and thermal store should be sized for optimum economics as this will in turn result in achieving the maximum CO_2 saving.

Unlike heat which is unregulated in the UK, electricity cannot be sold directly to consumers via a 'private-wire' network without providing third party access. This is seen as undermining a stable revenue stream for small scale CHP generators (Hawkey, 2012; Kelly et al, 2010). Many residential CHP installations are therefore restricted to supplying electricity to the central plant room and other landlord services within the development (e.g. pumps, communal lighting, lifts etc). Although this facilitates the economics of onsite CHP, the onsite electrical loads could be below the generation capacity if sized to the buildings thermal load.

The examination of the research presented has shown that CHP feasibility is linked to economic viability as much as technical efficiency. The associated high financial risks with capital investment, fuel costs and other technical factors (plant efficiency, temperatures of supply and return fluids, distribution losses and consumer heat loads) all affect the short and long term viability (Rezaie et al, 2012). Kelly et al, (2010, p.18) recognise that for small to medium scale CHP plant exporting electricty is prohibitively expensive. The analysis suggests that the Government and LPAs need to aid viability with support frameworks and policies to overcome financial barriers (Hawkey et al, 2013; Kelly et al, 2010; Lund et al, 2000; Mroz, 2008).

3.6.5 UK Carbon Emissions Factors

SAP calculates the CO_2 savings from CHP on the basis that each unit of electricity generated offsets a unit of electricity that would have been imported from the national grid (Allison, Bird & Ozmumcu, 2016). The carbon intensity (gCO_2/kWh) of the UK electrical grid is therefore directly related to the CO_2 saved by a CHP. As the carbon intensity of the national grid decreases so does the potential CO_2 saved from a CHP. While CHP in a HN is predominantly fueled by natural gas, the UK electrical grid is fueled by a complex and varied array of sources, including RE.

The SAP emissions factors are used by building designers to demonstrate compliance with ADL1 and importantly for this research planning conditions through an ES. The current SAP (2012) uses a carbon intensity based on a three year average factor (519 gCO_2/kWh). However, while the intensity factors for single use fuels or conversion technologies (e.g. natural gas CHP) remain relatively constant over time, the UK grid factor changes constantly as the supply sources changes (Allison et al, 2016; Crane, 2018). The current average CO_2 factor for the UK electrical grid is below the SAP and is expected to continually decrease overtime (Crane, 2018). In 2014 the factor was 394 gCO_2/kWh and by 2019 the grid carbon intensity factor is predicted to be 300 gCO_2/kWh respectively (Allison et al, 2016). This reduction can have a significant impact on the CO_2 saving potential of CHP compared to other technologies and thus lead to designer's consideration over other technology selections (ibid). Figure 3.10 illustrates the past, current and future predictions of grid carbon intensity, as well as corresponding technology carbon intensity performance.

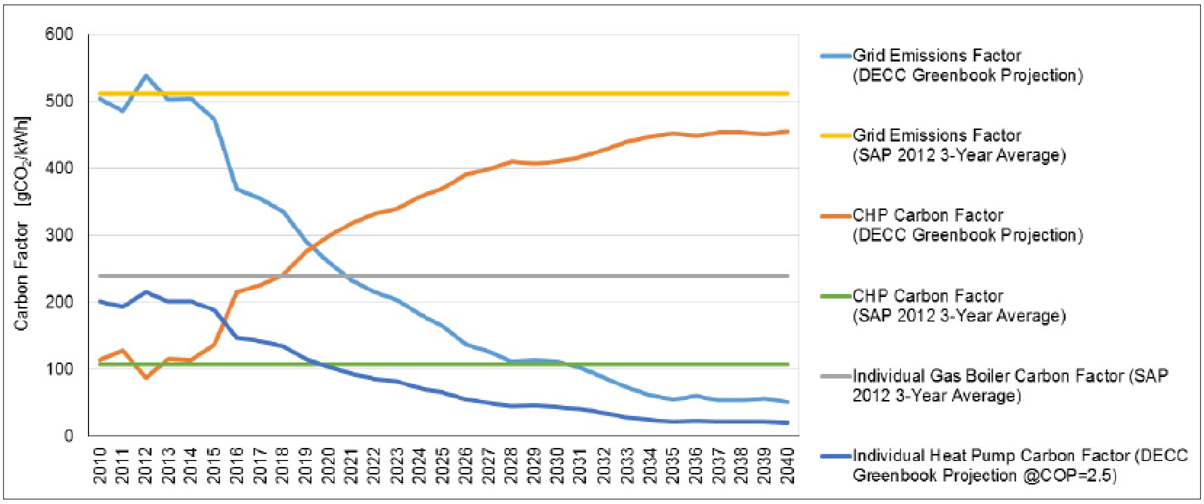


Figure 3.10: UK Carbon Factors – Past, Current and Predicted (Allison et al, 2016)

The GLA recognises that the grid emissions factor 'fluctuates', but states that an ES must adopt the same carbon factors as current the building regulations (GLA, 2016). As has been shown over time this could lead to inaccurate predictions of the CO_2 reductions. Allison et al (2016) calculated the CO_2 saving from CHP compared to a 'business as usual' case (i.e. individual gas boilers). Based on the SAP (2012) three year average carbon intensity (519 gCO_2/kWh) they calculated a saving of 137 gCO_2/kWh or 60% improvement over heat from a conventional individual boiler. However, a CHP is only calculated to save CO_2 emission compared to individual boiler when the grid carbon intensity is above 300 gCO_2/kWh. On the current projections grid carbon intensity is expected to be below this by 2019/2020 (ibid). Figure 3.10 illustrates the effect on CHP performance as grid carbon intensity reduces. CHP is shown to increase CO_2 over individual gas boilers in 2018/2019 and direct grid electric heating in 2019/2020. However, the GLA's adoption of SAP (2012) carbon factors will continually show a positive CO_2 reductions from CHP.

Crane (2018) argues that despite reduced grid carbon intensity factors, CHP can still achieve CO_2 savings. He argues that CHP and sufficient thermal storage is fundamental to achieving good economic and environmental performance; by optimizing run times and using bespoke carbon factor on a half-hour basis CHP can be evaluated to reduce CO_2 between 32% and 46%.

3.6.6 Feasibility Assessment for HN-CHP

The review of the available research has identified that appropriate feasibility analysis is essential to the success of HN-CHP developments (Lund et al, 2005; Laajalehto et al, 2014;

Rezaie et al, 2012). Crane, (2018, p.15) states that "*CHPs sized on 'rule of thumb' do not lead to maximum economic returns or highest CO_2 savings*"

Huang & Yu, (2014, p.110) argue that that planning cannot be a "*final solution*", only a reference to a planning decision and that analysis models will never consider all collective factors that could be considered. Furthermore economic, technical, spatial, and social factors will require "*readjustment*" for "*optimization*" of systems when "*designers make a designs*" (sic). This approach is support by Rezaie et al (2012) who suggested that the technical parameters (fuel choice, plant size, network configuration) set by '*Government action'* were three time more likely to affect performance, than the managerial operation of the plant. The industry recognises that at the detailed design stage of a project a more detailed evaluation of environmental impacts and benefits will be required to support a planning application, to comply with legislation and to make the case for the project in terms of CO_2 reductions (CIBSE, 2015).

3.7 Chapter Reflectance

This chapter has engaged with the academic research and industry guidance to introduce the technologies of HN and CHP. A description of each technology and their historical use within the UK was provided. It was identified that there has recently (post 2010) continued to be an increase in number of installed good quality CHP year-on-year within the UK, which coincides with the promotion of the technology within national and local planning policy.

The chapter also examined how these technologies are expected to combat the three challenges the UK faces with the supply and use of energy: climate change; security of supply; and fuel prices. The benefit of higher plant efficiencies, flexibility of fuel supply and long terms aims of integrating RE technologies was identified as the major benefits HNs. While the co-generation of heat and power with lower primary fuel consumption, generators closer to consumers, and to provider a return on investment through the sale of exported electricity were identified as benefits of CHP.

The final section of the Chapter explored the methods for conducting feasibility assessment of these technologies. It was shown that the feasibility of these technologies was not only a technical consideration but also one of economic feasibility. A buildings HD and LHD are fundamental to the feasibility of a HN. For CHP, it was identified that it is important to examine a range of sizing methods (thermal and electrical) and capacities to maximise the potential for CO_2 reductions and minimise economic payback. It was identified that heat is considered the primary focus when sizing CHP for CO_2 reductions; however, unless the electrical demands are considered the economic feasibility of a CHP is at risk. The risk is increased through the limited access to electricity markets that small-scale CHP have to generate revenues and are generally limited to supplying low demand areas of buildings. It was shown that SAP electricity carbon intensity factors are above the current average of the UK electricity grid. The grid carbon intensity is projected to reduce over the next few years and decades. These factors will influence how these technologies compare to tradition forms of heating (i.e. individual gas boilers) in terms of energy, CO_2 and fuel costs.

CHAPTER 4: THE ENERGY PERFORMANCE GAP

This chapter introduces the term energy performance gap in relation to the energy use in buildings. The complexities regarding the prediction and measuring of energy use in buildings is discussed and why it is important to recognise the energy performance of buildings. This section then outlines the factors commonly attributed to the existence of a gap and actions that are available to minimise the gap.

4.1 Definition of the Energy Performance Gap

The 'Energy Performance Gap' is defined as the difference between the designed energy performance (as calculated) and the energy use of a building once operational (De Wilde, 2014). It is important to recognise that variations in calculated energy and energy consumption in practice is inevitable due to inherent flaws in predictions and measurements. However, presently the gap is considered 'too wide to be acceptable' (De Wilde, 2014 p.40; Van Dronkelaar et al, 2016).

"*every new piece of construction is to some extent a hypothesis and its performance in practice is the experiment*" – Bordass et al, (2004 p.7).

It is also important for the context of this research to appreciate that the use of energy and the emission of CO_2 are linked. If building energy consumption is higher than predicted, then its CO_2 will also be higher than predicted – when referring solely to CO_2 emissions this would then be the 'CO_2 performance gap' (NHBC, 2012). The term 'performance gap' can also be used to define the in-use performance of any design element being analysed. For instance; the efficiency of a boiler; the thermal performance of wall insulation; the lux levels of lighting, etc. This research is focused on the EPG (and resultant CO_2 performance gap) of HN-CHP to deliver regulated energy[10] for space heating and hot water production in residential buildings. The research does not include the assessment or the effects of non-regulated energy[11].

[10] Regulated Energy – energy demands assessed under Building Regulations Part L1A: space and water heating, ventilation fans, water pumps and fixed lighting.

[11] Non-regulated energy - energy demands not assessed under Building Regulations Part L1A: domestic 'plug-in' appliances, portable lighting, cooking, etc.

Initially the concept of the EGP appears straight forward - a gap existing between the predicted value and measured value; however, the real-world design, construction and measurement of buildings is complex. There are various approaches of both prediction modelling and measurements, with regulatory compliance adding further complexity (De Wilde, 2014). Table 4.1 characterises different types of prediction and measurement methods. The type of EPG being examined dictates the approach to measurement and analysis. This research is focused on Type 1 and 3, where regulatory models (semi-dynamic) are used to demonstrate compliance with ADL1 and TLP Policy. Type 2 is not relevant to this research as this type of modelling is not used in the planning stage and detailed design stage of energy use within buildings.

The EPG is also considered to be a *'credibility gap'*, as performance differences (whether actual or perceived) can reduce the confidence of industry and the general public that low energy buildings can be delivered and worth the additional capital expenditure (Bordass, 2004; De Wilde, 2014).

Table 4.1: Three Types of Energy Performance Prediction and Measurement Methods (De Wilde, 2014):

Type	**Description**
Type 1: Differences between 'first-principle' energy models and actual building measurements.	Using information about the proposed buildings physics and systems to create a computational model, which is used through computer calculations or simulations to generate predictions. Model can vary from simple stationary calculations (utilising fixed monthly or annual averages), semi-dynamic simulations, to full dynamic simulations (dynamic changing values in hourly time steps). Input details and model complexity increases when moving towards more dynamic models. First principle modelling forms the basis of most energy performance predictions.
Type 2: Differences between machine learning approaches and actual building measurements.	A lesser used energy performance prediction method, known as machines learning. This method uses techniques such as artificial neural networks and regressive analysis to develop a coloration between input parameters and output parameters. Consequently, large amounts of machine 'training' data is required through measurements.
Type 3: Differences between regulatory compliance tests energy models and actual building measurements (displayed via energy display certificates).	While the calculations methods used in regulatory compliance have their basis in the semi-dynamic calculations methods as seen in type 1; there are fundamental differences in the design approach. Regulatory compliance prediction methods require designs to be set against unambiguous ranking scale with a clear pass-or-fail benchmark. Measurement in regulatory compliance is taken

	from meter readings and translating these into Energy Use Intensity (EUI) figures for comparison across the wider building stock. These measurements inherently include energy use of plug loads, occupant behaviour and climate variation. Whereas, regulatory prediction typical only considers heating, cooling, ventilation and lighting loads, calculated from average monthly figures. This difference in prediction and measurement methodology creates an automatic performance gap.

4.2 The Energy Performance Gap Research

The available research and industry studies related to the EPG is now examined. The review is focused on research related to the space heating and hot water generation and resultant energy consumption in residential buildings, although the wider literature on the EPG are discussed where appropriate to this research. The type and context of an EPG is explored and how these are affected by the energy data available. The present understanding of the causes and current efforts are being made to minimise the EPG are presented.

4.2.1 Identifying and Quantifying an Energy Performance Gap

It has been discussed (chapter 2) how building regulations, planning policy and sustainable buildings assessments schemes have driven the transition to low carbon design. However, as observed, these methods focus on primarily on design intent, rather than performance in practice. The practice of identifying an actual building performance is Post-Occupancy Evaluation (POE) (Li, Thomas and Froese, 2018).

A gap in performance is typically identified through a POE when a building has been operational and occupied for some time; typically one year. The CIBSE PROBE studies were some of the first major POE review of buildings. The studies ran between 1995 and 2002 and were conducted on a range of non-domestic buildings. It was found that, although nearly all of the case studies claimed to be energy efficient, the range of annual consumption and CO_2 varied widely, with buildings using twice as much as predicted (PROBE, 1999; CIBSE, 2012). Since PROBE the EPG has become an expanding field of research, with recent evidence finding energy use up to three times that of the design expectation (Osmani & O'Reilly, 2009; Thomas & Duffy, 2013; De Wilde, 2014;).

Before an EPG can be identified it is important to first recognise the common metrics that the energy use and CO_2 are being compared with (Carbon Trust, 2011). A common metric is the *regulatory* model, defined as type 3 (see table 4.2). The regulatory model uses a 'Simplified Building Energy Model' (SBEM) or the 'BRE Domestic Energy Model' (BREDEM), as the basis of energy (kWh/m^2/year) and CO_2 (kgCO_2 /m^2/year) calculations for ADL1 compliance. Importantly for this research the regulatory models are also the basis for demonstrating compliance with TLP.

As illustrated in figure 4.1, regulatory models do not take account of all consumed energy within a building or the variation in use and operation of the building. Therefore to simply compare total energy consumption (e.g. through utility meter data) of a building with its regulatory model, will inevitably result in an EPG (De Wilde, 2014, p.44). Although Wilde (2014) does not overlook the stark difference between compliance models and actual energy consumption; figure 4.2 provides comparisons of twenty non-domestic buildings that had received strong environmental credentials (BREEAM and RIBA sustainability prize). Only two of the twenty reported the same energy performance rating (A-G) between the compliance rating (Energy Performance Certificate) and the actual building energy consumption (Display Energy Certificate). Van Dronkelaar et al (2016), argue that the EPG could be significantly reduced if an energy simulation is conducted taking detailed account of the building context. They define this as 'performance modelling'. A performance model includes all quantifiable energy consumptions with the aim to maximize accuracy. Further calibration techniques are being adopted to 'fine-tune' models to operation and energy use; these models are used to identify underlying causes (Van Dronkelaar et al, 2016).

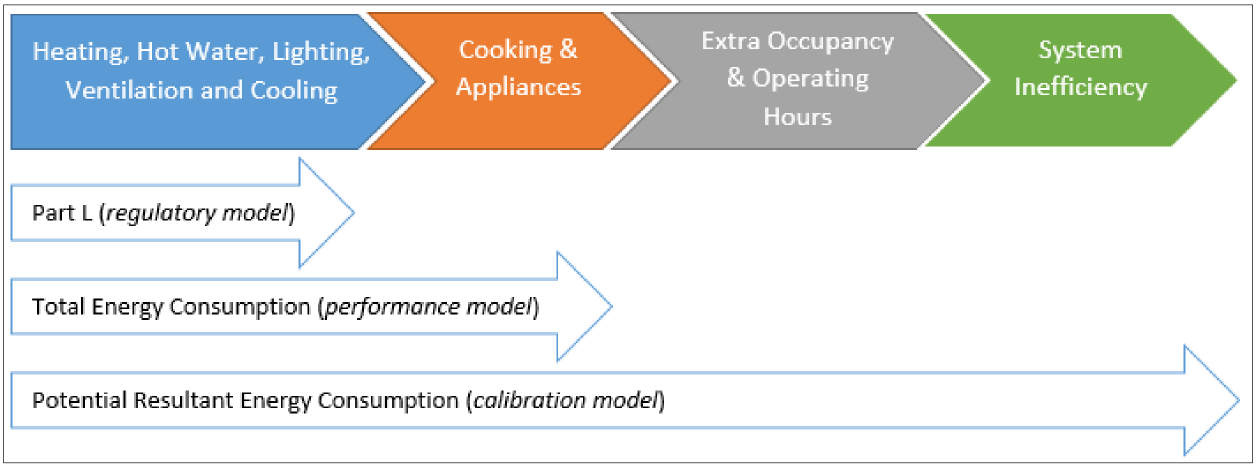


Figure 4.1: Regulatory Model versus All Consumed Energy in a Building (adapted from Carbon Trust, 2011).

	Credentials	Building type	EPC	DEC
building 1	BREEAM Excellent	court	B	D
building 2	BREEAM Excellent	court	B	E
building 3	BREEAM Excellent	data centre	A	F
building 4	BREEAM Excellent	education	B	F
building 5	BREEAM Excellent	education	B	D
building 6	BREEAM Excellent	education	B	D
building 7	BREEAM Excellent	office	B	C
building 8	BREEAM Excellent	office	A+	E
building 9	BREEAM Outstanding	education	B	G
building 10	BREEAM Excellent	court	D	D
building 11	BREEAM Excellent	education	C	C
building 12	BREEAM Excellent	education	B	C
building 13	BREEAM Excellent	education	B	E
building 14	passivehouse	education	A+	B
building 15	concrete center case	education	B	E
building 16	concrete center case	education	B	F
building 17	RIBA prize	office	A	B
building 18	RIBA prize	office	B	C
building 19	RIBA prize	healthcare	B	E
building 20	RIBA prize	education	B	D

Figure 4.2: Comparisons of Legislative Energy Assessment in Non-domestic Buildings (De Wilde, 2014 p.44 fig.3)

When comparing measured energy with a regulatory model it is therefore essential to compare 'like-for-like' energy consumption or where available use sub-metering to accurately record the consumption of specific systems covered by the regulatory model (e.g. heating). For residential buildings the regulatory model is the SAP assessment. There are examples of energy consumption for space heating (SH) and domestic hot water (DHW) being compared with the predicted performance of the SAP to identify an EPG (Burzynski et al, 2012; Sodagar & Starkey, 2015; Gill et al, 2010; Gaze, 2014; Littlewood et al, 2014). These examples identified a wide variance in energy performance when compared against the SAP, with a mix of good (consumed less energy than predicted) and poor performing buildings.

Within a single study there can be a vast difference in the amount of energy consumed by dwellings of the same size and type, demonstrating the influence that occupants have on energy consumption (Burzynski et al, 2012; Sodagar et al, 2015; Zero Carbon Hub, 2015; Gill et al, 2010; Delzendeh et al, 2017).

The examination of the research has identified that the term EPG can be easily generalised, which may inadvertently mislead the reader on the type or cause of the EPG that is being observed. For instance, where only the primary fuel (e.g. gas) consumption was analysed, SH and DHW energy consumption could only be considered at a system level (Sodagar et al, 2015; Gill et al, 2010). In these studies the EPG was established based on the quantity of primary fuel used and therefore the efficiency of the heat source (e.g. gas boiler) is included within the comparison against predicted performance (SAP). It was not possible to differentiate between the useful heat energy required (for SH and DHW demand) and the energy lost by the heat source when converting the primary fuel to useful heat. There are currently only a few studies (see Burzynski et al, 2012; Gill et al, 2010) that use data from HMs that provides data on the useful heat consumption of the dwelling, as energy is measured after the primary fuel conversion. In both types of research the identified EPG was just defined as heat.

Many of the studies adopted a method to differentiate between the energy consumed for SH and DHW. The method was to identify periods where SH was unlikely to have occurred (e.g. summer), the energy could therefore be presumed to be for DHW only. For the remaining period the presumed value for DHW could be subtracted from the total energy to proportion SH (Burzynski et al, 2012; Sodagar et al, 2015). Figures 4.3 through to 4.6 present findings of selected studies on the variance in EPG when compared to the SAP predicted energy consumption for SH and DWH. These figures demonstrate that heat energy use can vary significantly between users. Furthermore, that consumption typically follows a seasonal curve.

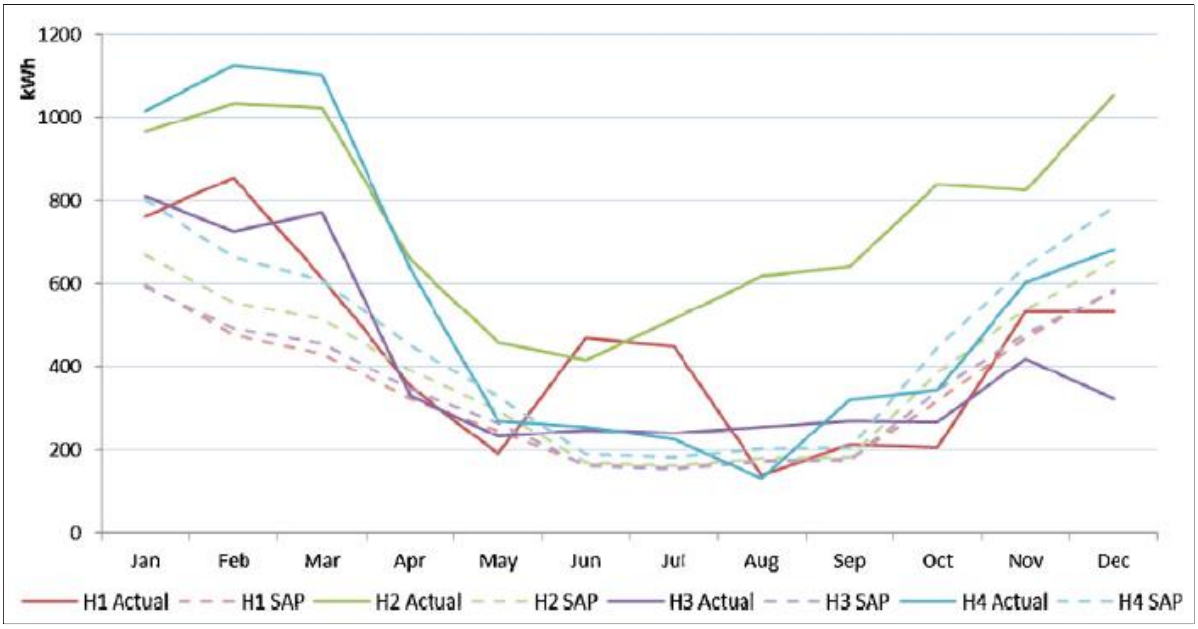


Figure 4.3: Primary Energy (Gas) - SAP versus Actual (Sodagar et al, 2015, p.252 fig.10)

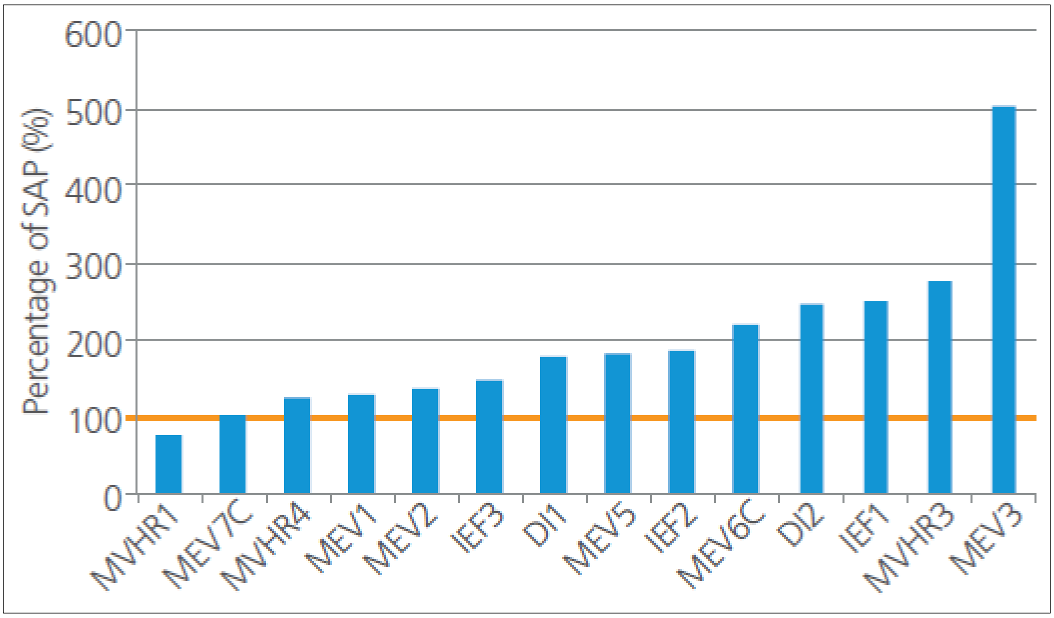


Figure 4. 4: Energy Consumed by Space Heating SAP versus Actual (Gaze, 2014, p.9 fig.3)

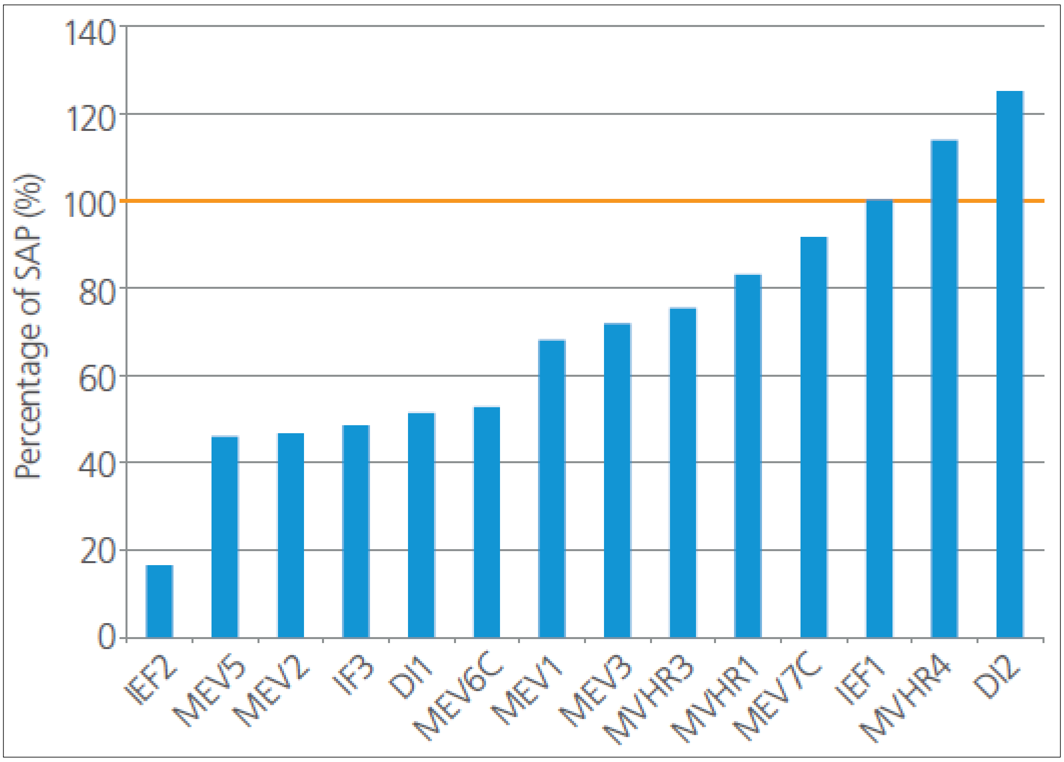


Figure 4.5: Energy Consumed by Domestic Hot Water - SAP versus Actual (Gaze, 2014, p.15 fig.23)

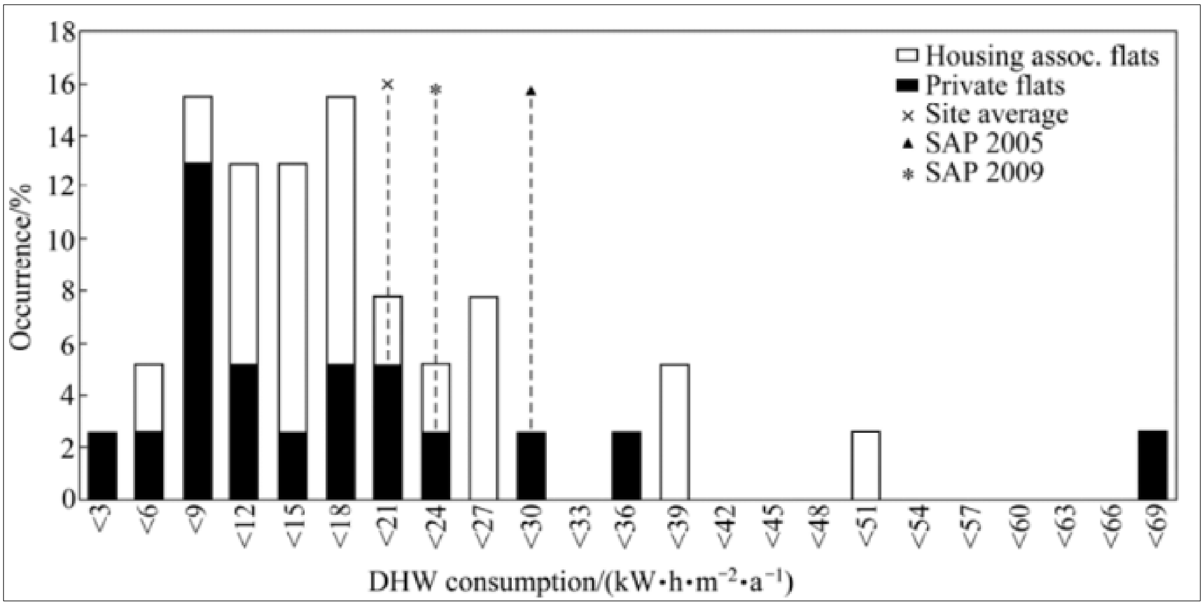


Figure 4.6: Distribution Domestic Hot Water Energy Consumption for 3 Bedroom Flats - SAP versus Actual (Burzynski et al, 2012, p.1633 fig.2)

4.2.2 The Measured Energy Performance of Heat Networks and CHP

There have been recent calls for the energy performance of HN-CHP to be examined following a number of anecdotal reports of poor energy performance. Industry, local government and the UK Citizens Advice have all expressed concern regarding the lack of available data on the energy performance; viability as a low carbon technology; and the value for consumers (Watts, 2015; Housing Select Committee, 2015; Citizens Advice, 2016). The Housing Select Committee (2015) raised concerns that the "*decentralised energy policies being driven by the GLA appeared to the Committee, to be without thorough evidential foundation."*

From the academic literature examined only Burzynski et al (2012) and Gill et al (2010) measured the energy consumption of dwellings connected to a HN and compared it directly to the design (SAP) predictions. However, in these studies only the domestic heat energy (SH & DHW) was analysed and not the performance of the HN. Their research is unique as they evaluate the 'useful' heat requirement of the dwellings (for SH and DHW) demand and therefore provides data on the effectiveness of the SAP assessment to predict heat demand and hot water consumption in new dwellings.

Research by Burzynski et al (2012) compared the measured heat energy consumption with two versions of the SAP assessment (2005 and 2009) to analysis and quantify the EPG. Their analysis showed that there was a gap for DHW with dwellings on average using between 50% and 100% less energy than predicted by SAP 2005 and 28% to 68% less compared to SAP 2009; this indicates the SAP was not particularly accurate at predicting the DHW energy consumption, however, the 2009 version was more accurate than the 2005 version. For SH the opposite was found, the dwellings used more energy than predicted (31%) by the SAP 2005 (SAP 2009 was not analysed). Overall, the difference from predicted energy for SH and DWH was only 8%. These results were similar to those presented in figures 4.4 and 4.5. Burzynski et al (2012, p.1638) argues that this EPG is important as the SAP predictions could have led to the thermal store and CHP being incorrectly sized. Table 4.2 demonstrates the energy consumption compared to the SAP prediction. Burzynski et al (2012) study is relevant to this research as it provides a method for comparing measured heat energy consumption against SAP predications and illustrates how SAP is used in both the design and evaluation of dwellings connected to a HN.

Table 4.2: Monitored Annual Energy Consumption for Domestic Hot Water in Flats Connected to a Heat Network Compared to the SAP Assessment (Burzynski et al, 2012)

No. of Bedrooms	**Site DHW Consumption**	**DHW SAP 2005**	**DHW SAP 2009**
-	(kWh/m^2/a)	(kWh/m^2/a)	(kWh/m^2/a)
1	19	37	32
2	15	30	25
3	18	27	23

Gill et al (2010) analysis of dwellings connected to a HN found a level of deviation in heat consumption between dwellings. The study found a site average of 23% reduction in heat energy consumption (kWh/m^2/year) compared to the SAP prediction. The study also compared the findings against a post-construction dynamic simulation model where post occupancy information (occupancy levels, etc) was used and the gap was then found to be only 6%.

From the available residential POE the focus is on the domestic level (SH and DHW) energy consumption and these have shown a wide variation in energy consumption between dwellings. Of the research conducted on dwellings connected to a HN, the findings have predominately found that domestic heat energy use is below that predicted in the SAP. This would suggest that the dwellings are typically performing better than expected and would therefore be expected to have lower CO_2 related to domestic heat. However, the POEs did not analyse the energy performance of the overall HN. Neither did they compare the performance with the SAP or the planning policy targets. According to Watts (2015) this makes the prediction of HN-CHP systems viability very difficult.

Industry research is becoming more prevalent at identifying EPG in HN-CHP through POE. The results are more commonly being shared as secondary data, on open platform sources such as the Carbon Buzz, Zero Carbon Hub and Building Data Exchange. Some of these industry POE research relating to HNs and HN-CHP are examined next.

Utilising an online search engine identified a number of anecdotal articles of poor performance and high heating bills related to HNs. One online article cited two HNs with efficiencies of 37% and 61%, despite being assessed as 90% (YouGen, 2014). A POE study available through the open source website Building Data Exchange [accessed April 2018] examined the in-use performance of a 173 dwellings connected to a HN-CHP (and additional biomass-boiler) system. The study identified that the demand for heat at domestic level (SH and DHW) was lower than the SAP prediction, suggesting a higher performing low carbon building; however, a poor energy performance of the overall HN-CHP system lead to a significant increase in energy consumption (AECOM, 2014). The investigation used data from three dwelling level HMs and compared it with the energy consumption prediction of the three corresponding SAP assessments. Their findings (figure 4.7) demonstrate that the heat demands were lower than those predicted by the SAP. It must be recognised that the data was only analysed from three flats and therefore it is difficult to generalise these findings across the entire building. For instance, Burzynski et al (2012) and Gill et al (2010) research has shown a large standard of deviation can occur in heat demand between multiple dwellings.

The POE concluded that the performance of the HN was considerably worse than expected, the heat loss of the distribution system was measured to be 69%. The efficiency of the HN-CHP system from primary energy consumption compared to delivered heat was found to be only 26% for the same period (AECOM, 2014, p.70). The author identified that the difference between generated and delivered heat (i.e. heat loss) decreased and system efficiency increased in the winter period compared to the summer, they attributed this to an increased heat demand (i.e. heat density). The conclusion of the POE was that the dwelling CO_2 emissions rate ($kgCO_2/m^2$/year) was significantly higher than predicted by the SAP. This was a result of the poor HN efficiency and the 'low carbon' heat sources (CHP and Biomass Boiler) not operating during the period. The author's expectation that greater efficiencies will be achieved once the CHP is operational provides an example of how CHP is perceived as fundamental to the energy and CO_2 performance of HN (ibid, p.4). The author of the POE noted that the ES did not change from concept design to pre-construction and the installed biomass capacity (kW) increased only as a result of the preferred manufacture's equipment range, rather than a recalculation of energy requirements (Ibid, p.10).

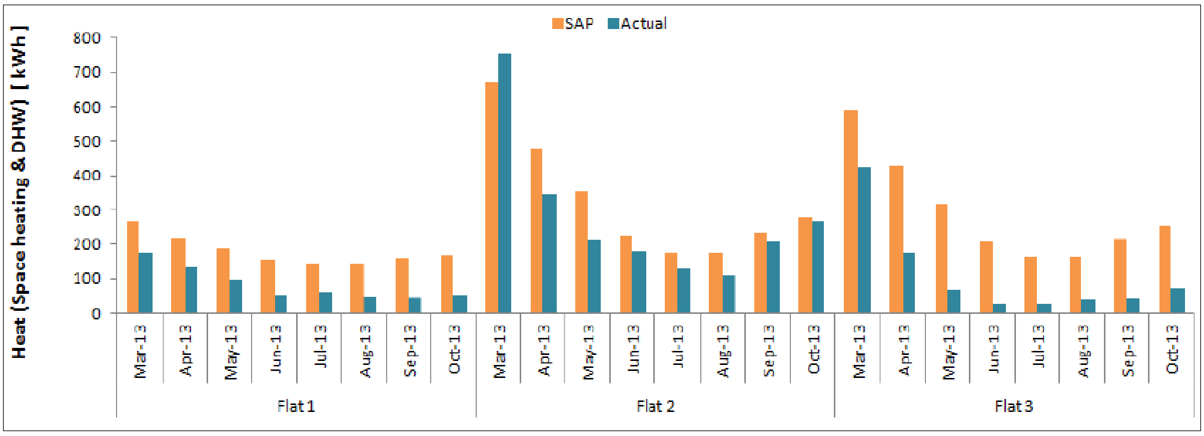


Figure 4.7: Actual Dwelling Heat Meter Data (SH and DHW) and SAP Predictions for March to September 2018 (AECOM, 2014, p.66 fig.7.16a)

University College London (UCL) and professional engineers AECOM, completed POEs on residential developments containing HNs. One included a HN-CHP (AECOM, 2014) and the other a HN-Biomass boiler system (UCL, 2014), both developments at planning stage were expected to have a high energy performance. The two planning stage ES reports stated there would be a 19% reduction in onsite CO_2 from the CHP (HN-CHP scheme). The HN-Biomass scheme would be net zero carbon with SH and DHW demand of <75 kWh/m^2/year. The normalized heat demand for the HN-Biomass scheme calculated that the average demand for both SH and DHW was 33.2 kWh/m^2/a; considerably below the designed 75 kWh/m^2/year (UCL, 2014, p.98). Five of the dwellings measured (a small sample) had a wide variation in SH (6.0 to 57.7 kWh/m^2/year) and DHW (4.8 to 26.6 kWh/m^2/year). Although the analysis is from only a small sample the findings were consistent with those found in other studies. These findings showed that dwellings have a wide variation in consumed heat energy and that dwellings connected to a HN generally have a lower than predicted heat demand (AECOM, 2014; Burzynski et al, 2012; Gill et al, 2010).

The HN energy performance of both schemes were found to be significantly worse than predicted. Table 4.3 uses the data from the two studies and demonstrates the energy performance of the HN systems, including the lower than expected efficiency of heat generation, high distribution heat losses (DHL) and high electrical consumption for pumping. The author of the HN-Biomass POE noted that the designer’s estimation of DHL were not provided (UCL, 2014, p.102).

The HN-CHP scheme did not achieve a 19% reduction in CO_2 from the CHP as predicted in the planning ES. The CHP did not run during the monitored period, although the predicted savings would have likely been outweighed by the increase in CO_2 resulting from the high DHL. The HN-Biomass scheme exceeded the domestic level performance for SH and DHW demand, but again these savings were outweighed by the DHL.

These two POE studies have identified that although domestic heat energy consumption has been less than predicted, the use of a HN has resulted in higher overall CO_2 (UCL, 2014). The POEs examined here show that the scale of DHL decrease as HD increases (AECOM, 2014; UCL, 2014). These findings can be related to the literature examined in chapter 3 that showed DHL as a function of LHD (see section 3.6.2). None of the POE examined discussed the building HD or LHD. UCL (2014) state there is a need for further research to understand the efficiency and effectiveness of HNs.

Table 4.3: Comparison of Two Heat Networks (adapted from AECOM, 2014 p.70; 2014a p.103)

Form of Energy	**Units**	**HN-CHP**	**HN-BIOMASS**
Total Primary Fuel	kWh	2,141,993	-
Gas Boiler Heat Generation	kWh	1,820,694	593,810
Biomass Heat Generation	kWh	0	376,940
CHP Heat Generation	kWh	0	N/A
Total Heat Generation	kWh	1,820,694	970,750
Heat Generation Efficiency	%	85	-
Heat Consumed	kWh	567,009	399,582
Generated to Delivered Heat	%	31%	42.2%
HN Distribution Loss	%	69%	58.8%
Overall Thermal Efficiency	%	26.5%	-
HN Electrical Energy Consumption	kWh	-	57,618
Percentage of Heat Generation	%	-	5.9
Percentage of Heat Consumption	%	-	14.4

The government has recognised the need for more evidence based knowledge on HNs and subsequently commissioned a report to assess the costs, performance and characteristics (DECC, 2015). As part of this report seven existing HNs were identified with sufficient data available to report on the DHL and auxiliary energy consumption. The overall HN efficiency, performance of heat sources (e.g. CHP) and comparison with predicted consumption (SAP) were not given. Four of the existing HN were classified as 'bulk' (district HN supplying to a building interface only, not final individual consumers within the building) and three were 'non-bulk' (small-scale HN supplying heat within a building to final consumers), the non-bulk networks are relevant to this research. Of the three non-bulk, the report calculated DHL of 12%, 28% and 43%. The AE consumption was 1.9%, 2.0% and 1.7% respectively. Referring to the previous examination of the design guidance these values exceeded the expected performance of HN for DHL (<10%) and electricity consumption (<1.5%). Despite the poor HN performance, their report concluded that a HN with a CHP would lower CO_2 compared to an individual heating systems (gas boilers) and most other LZC technologies. However, the reduction in CO_2 is directly dependent on the amount of displaced grid electricity from the CHP and CO_2 factor used for electricity ($kgCO_2/kWh$) (DECC, 2015, p.38-39). The report recognises that a CHP will only provide a proportion of heat demand with the remainder met from other heat sources. Furthermore as a result of DHL, CO_2 savings would not be achieved in practice (ibid, p.38-39). The report provides a graph of CO_2 factors for a range of heat generation technologies; however, the graph does not illustrate the CO_2 heat intensity (gCO_2/kWh) for a HN. UCL (2014a) in their POE of a HN calculated a carbon factor of $500gCO_2/kWh$. Adding the HN to the carbon factor for CHP or Biomass Boiler (two technologies requiring a HN to serve multiple dwellings) would result in a significantly higher carbon factor than presented in the DECC report.

Table 4.4 and figure 4.8 calculates a heat CO_2 intensity (gCO_2/kWh) of a theoretical HN. The figures used are based on the average performance figures for DHL (29%) and electricity parasitic consumption (1.9%) measured by DECC (2015). The graph shows that a HN supplied by gas boilers would have a higher CO_2 intensity than conventional individual gas boilers. Due to the auxiliary consumption of a HN, the heat CO_2 intensity will increase as electrical CO_2 intensity increases. This illustrates the importance of accurately predicting DHL and auxiliary consumption when considering the feasibility of a HN for a new building.

Table 4.4: CO_2 Heat Intensity of a Theoretical Heat Network

Heat Demand (kWh/yr)*	5000	5000	5000	5000	5000	5000	5000
Distribution Heat Loss	28%	28%	28%	28%	28%	28%	28%
Heat Required (kWh/yr)	6400	6400	6400	6400	6400	6400	6400
Gas Boiler (85%)** Emissions Factor (gCO_2/kWh)	219	219	219	219	219	219	219
Gas Boiler (85%) CO_2 Emissions ($kgCO_2$/yr)	1402	1402	1402	1402	1402	1402	1402
Auxiliary Electrical Demand (1.9%) (kWh/yr)	95	95	95	95	95	95	95
Electricity Emissions Factor (gCO_2/kWh)	0	100	200	300	400	500	600
Auxiliary Electrical CO_2 Emissions ($kgCO_2$/yr)	0	9.5	19	28.5	38	47.5	57
Total CO_2 Emissions ($KgCO_2$/yr)	1402	1411	1421	1430	1440	1449	1459
Carbon Factor for Heat (gCO_2/kWh)	280	282	284	286	288	290	292

*Typical annual heat demand of a new build flat used by DECC (2015)
**Emission factor for an 85% gas boiler from DECC (2015)

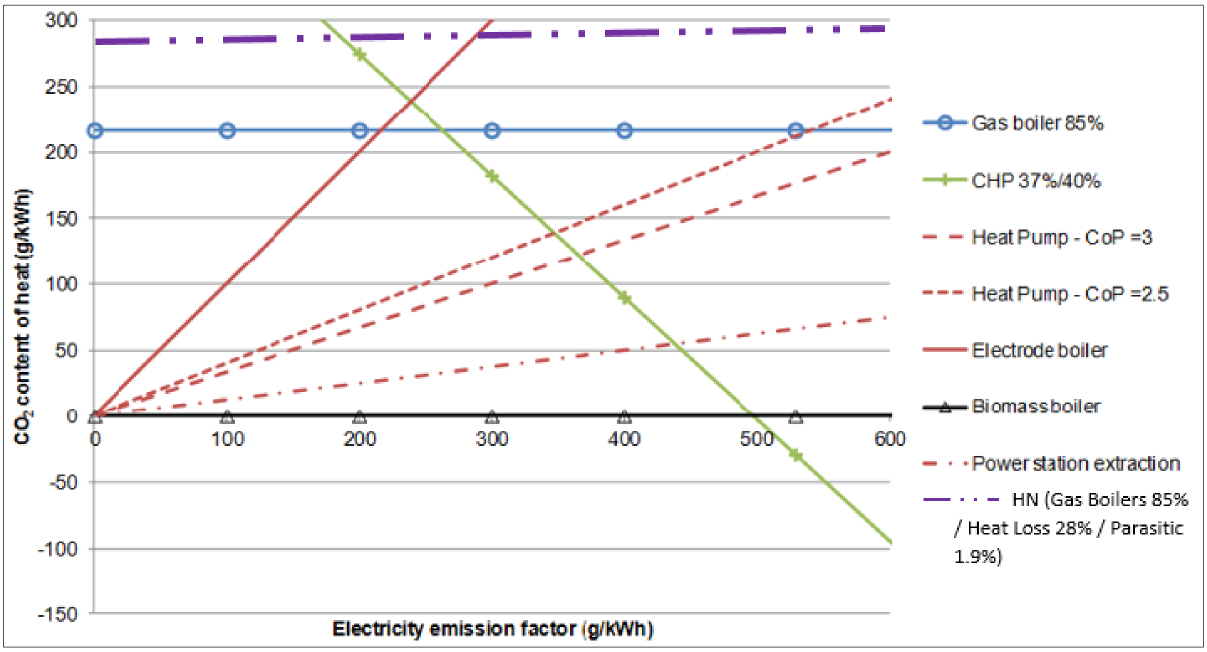


Figure 4.8: CO_2 Heat Intensity of Heat Generation Technologies (adapted from DECC, 2015)

The Building Research Establishment (BRE) created the BREDEM which is the calculation methodology used in the SAP assessment. As discussed in chapter 3 the SAP sets default values for a HN distribution loss factor (DLF) from 1.05 (5%) to 1.20 (20%) of total heat demand. BRE (2016) received feedback from third parties (developers and consultants) that the current default DLF were unrealistic, especially in new build apartments. In response BRE (2016) conducted an investigation to determine if the default DLF were representative of new residential buildings. Eleven case studies were identified and data collected to analyse the DHL (%) and DLF for each case. The findings identified that losses were between 23% and 66% resulting in DLF between 1.3 and 3.0. For one case study theoretical calculations of DHL were undertaken and calculated between 17%-20% subject to the network temperatures (^{o}C) used. BRE (2016) recognised that even theoretical losses were far higher than the SAP default (figure 4.12). This matches research conducted by Olsen et al (2008) who suggest that practical experience shows that real heat loss will be higher (20-30%), likely due to heat losses from fittings and components.

From their investigation BRE (2016) proposed changes to how the DLF should be calculated in future revisions of the SAP methodology. This included removing the three existing default value criteria (see section 3.6.2). The proposed change includes DFLs of 1.5 (33%), for schemes compliant with the CIBSE Heat Networks Code of Practice, and 2.0 (50%) for those not compliant (BEIS, 2016). Of the eleven case studies examined in the BRE report, three had DHL lower than 33%, eight had greater than 33%, and four had greater than 50% (ibid, p.5). The two POE examined in this section also reported losses in excess of 50%. These findings would suggest that even if these new DFL were introduced the DHL in many HN systems would not be accurately predicted and thus have an EPG. The Association for Decentralised Energy (ade) published a response to the SAP consultation (ade, 2017). The ade agreed that DLF should reflect available evidence, but disagreed with the new DFL proposed suggesting a lower figure of 1.3. ade consultation response included their own survey of DLF in existing HN, that showed a wide variation among different development types (figure 4.13). Notably all but one of the ‘smaller scheme- residential’ had a DLF higher than 1.2 (>20% loss); no definition was provided by the ade of what constitutes a smaller scheme.

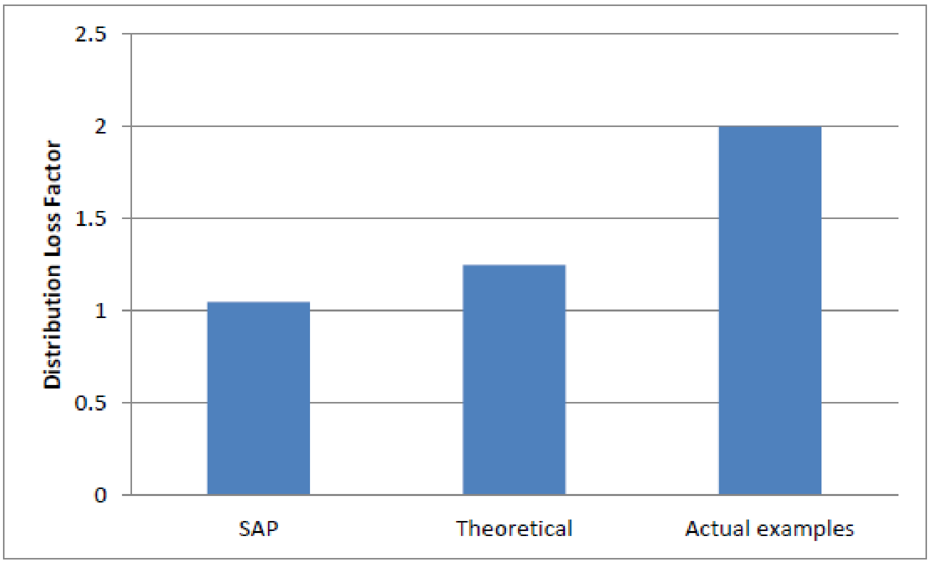


Figure 4.9: Comparison of Distribution Loss Factors (BRE, 2016)

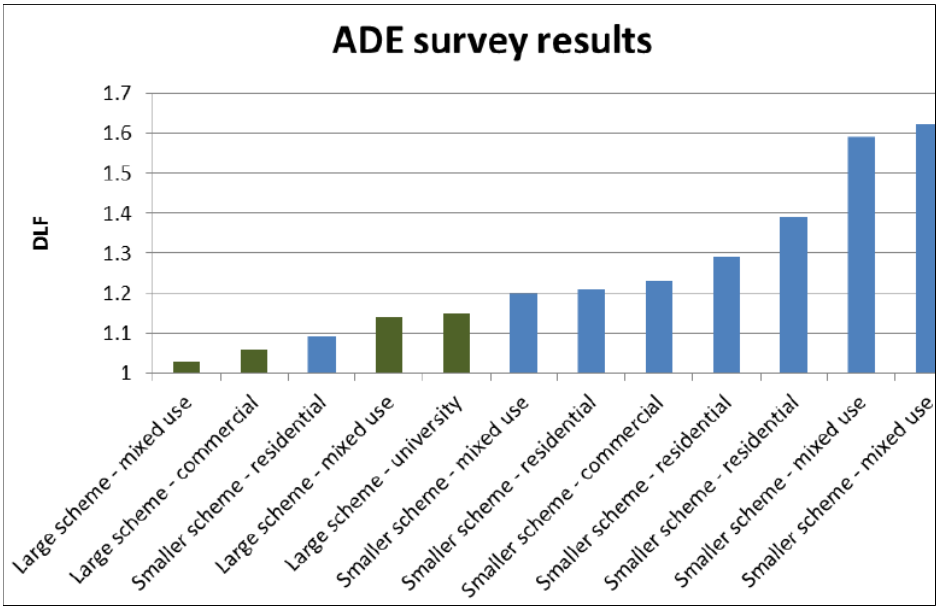


Figure 4.10: Survey of Distribution Loss Factors (ade, 2017)

Examination of the industry POE identified other issues that are being directly related to the HN. Although these phenomena are not directly related to this research, they are stated here for a context of the wider complexities of HN:

- Contributing to overheating in dwellings and communal corridors through distribution heat losses (AECOM, 2014);
- Lowering heat demand in dwellings through heat gain from distribution heat loss (AECOM, 2014; UCL, 2014)

4.2.3 The Present Understanding of the Energy Performance Gap

Examination of the present understanding of the EPG indicates there is a comprehensive range of contributing factors that span every stage of a project (De Wilde and Jones, 2014). The Zero Carbon Hub (2013) suggest that developers and planners have general lack of understanding regarding the impact their early stage decisions can have on design complexity and buildability. Van Dronkelaar et al (2016) believe that the early design choices (such selection of LZC) should be critically addressed during the concept design through sensitivity analyses that determine the impact of choices and prevent costly mistakes. Konidari (2017) identified the influence architectural design decisions have on a building heating consumption. Miscommunication and lack of information flow between the different actors, including feedback at the end of a project is considered a root cause of the EPG (Oreszczyn and Lowe, 2009; ZCH, 2013; De Wilde et al, 2014;).

The design itself is identified as an early issue: for instance, over-complicated design or controls, incorporating inefficient systems, inaccurate construction details, or lack of buildability (De Wilde et al, 2014). The inclusion of LZC technologies (identified as a requirement of planning) into the design are found too often have initial problems leading to an EPG (De Wilde et al, 2014). The PROBE (1999) studies suggested that designs often focused too heavily on LZC features and could lose sight of the overall building performance. They suggested that the symbolism of a low energy building could get the upper hand over the actual functionality.

Fundamental to the EPG is the accuracy of the modelling software used to predict the energy consumption of a building. This topic in itself is a comprehensive area of current research and therefore, it is not intended to be exhaustively presented here. Only the relevant research relating to regulatory modelling is examined.

Designers need to make sound decisions and use reasonable assumptions on the data they input into their model (De Wilde et al, 2014). The Carbon Trust (2011) report '*Closing the Gap*' notes that design predictions for regulatory compliance (i.e. building regulations) do not consider all energy uses in buildings (see figure 4.1), Menezes et al (2012) argue that this type of simplified modelling is the *"underlying causes of the performance gap"*. Van Dronkelaar et al (2016) also argue that regulatory models should not be used as a baseline for actual performance. However, Williamson (2012) identifies that regulatory calculations tools such as SAP are more likely to be used by designers and construction specialists over more complex design modelling software, owing to the SAP being the method required to assess compliance with building regulations, building control and other performance standards (e.g. planning conditions). Van Dronkelaar et al (2016) argue that the use of regulatory models was inevitable due to the dominance of the current regulatory framework in the UK.

It has also been found that errors can exist in the input data used in the SAP assessment. A sample of 82 SAP assessments nearly all had some level of error, which in 20% of cases would have resulted in the assessment failing to meet the design emission targets (UCL, 2014 p.130).

There is a clear acceptance that current models are completed using unrealistic input parameters (Bordass et al, 2004). Furthermore, specifications can be changed through ‘value engineering’ by the contractor or client, consequently the model data becomes inaccurate. Menezes et al (2012, p.357) state that many modelling assumptions go unchallenged and are made at a time when many aspects of the building function and use are unknown. Van Dronkelaar et al, suggest *“models represent a simplification of reality, therefore, it is necessary to quantify to what degree they are inaccurate before employing them in design, prediction, and decision-making processes”* (2016, p.3). To produce meaningful results, feedback must be applied to the models and effective knowledge gained to increase accuracies of future models. Menezes et al, (2012) adds that relying on tools alone, even corrected models, will be insufficent to close the gap. Designers must have the “knowledge and skill” to apply inputs appropriately (De Wilde, 2014 p.41). Currently there is no calculation or model audit trail.

The EPG exists, not just between the ‘as designed’ and ‘as built’, but also the ‘as managed’ stage of a project (Williamson, 2012). Insufficient commissioning of in-use requirements and/or seasonal variations; a lack of training of facilities managers; and overriding of settings to solve complaints, are common conclusions drawn in POE studies (Bordass et al, 2004; Williamson, 2012; Menezes et al, 2012; Goulden and Spence, 2015; Min et al, 2016). Bordass (2004) argues for a means of ‘consolidating’ knowledge gained (between clients, design and construction team, users, managers) into learning within each organisation or so called 'knowledge management'. The study identified from both clients and construction companies that they "*were not yet good at this*" (ibid p.6).

The present understanding of the EPG indicates that there is an opportunity for the EPG to be influenced at every stage of the project process, Bunn and Burnman (2015) presented the underlying causes of the EPG at the different stages of the RIBA plan of work. The S-curve model allows for easy visualization of the performance issues through the transient stages of a project and early stages of operation. Identifying the RIBA stage where a projects ES is created (figure 4.11), shows that this occurs at the peak performance point.

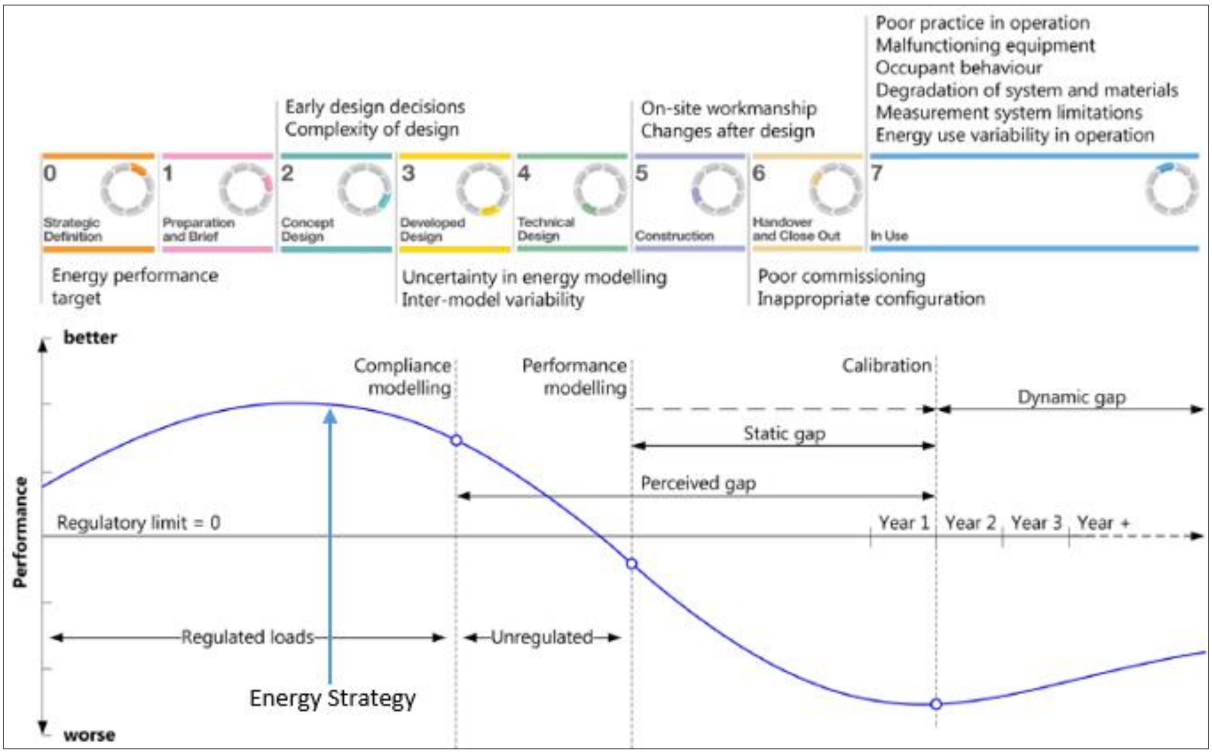


Figure 4.11: S-Curve Visualization of the Underlying Causes of the EPG in the different Stages of the RIBA Plan of Work (adapted from Van Dronkelaar et al, 2016)

4.2.4 Closing the Energy Performance Gap

Closing the EPG is vital to ensure that the domestic sector plays its role in achieving the CO_2 reduction targets set in UK and EU legislation (De Wilde, 2014; Magalhães & Leal, 2014). Evaluation of existing designs is also required to improve future designs, both in the sense of identifying and rectifying flaws in designs and calculations, but also to highlight designs that are performing better than expected. This is identified as feedback for planners, designers, contractors, and facility managers (Bordass, 2004; De Wilde, 2014; Menezes, Cripps, Bouchlaghem, & Buswell, 2012). As planning targets become increasing ambitious at lowering CO_2, the underperformance in design may soon be a legal or financial implication for designers (Van Dronkelaar et al, 2016)

4.3 Chapter Reflectance

This chapter introduced and defined the term EPG and its relation to the energy use and performance of buildings. It was found that there are different classifications of the EPG that are specific to the energy prediction model applied. The most common models are regulatory models that are used for compliance testing with Building Regulations and importantly for this research demonstrating compliance with planning energy policy. The differences of regulatory models (to *performance* or *calibration* models) and limitations were explained.

From the available research and POE evaluations examined non-domestic studies are prevalent, where an EPG of two to three times is commonly observed. Currently there is limited data relating to residential EPG and fewer still specific to HN-CHP. Of those examined there was significant variation in heat energy consumption, among dwellings of similar size, type and construction. The EPG was seen to vary widely between studies. Of those related to dwellings connected to a HN, it was identified that domestic heat demand is generally lower than predicted, suggesting the energy performance of these dwellings are better than expected. However, the performance of the HN was significantly worse than predicted with considerably higher DHL and auxiliary energy consumption than predicted. Where a CHP was included these were found not to be operational.

The causes of the EPG are present at every stage of the project process. Causes include:

- poor early design decisions
- miscommunication
- modelling issues
- inaccurate or overly complex design
- poor buildability of designs
- workmanship/installation errors and
- commissioning/control/management error

CHAPTER 5: RESEARCH QUESTIONS AND RESEARCH DESIGN

This chapter will provide justification for the research and its examination of the established knowledge gap. A primary research question is proposed which defines the research intent and boundary. Secondary research questions outline the direction of the research through incremental exploration of the research themes. This chapter details the journey through the consideration, evaluation and development of the research paradigm, methodology, and selection of methods suited to the collection of data within a 'real world' environment. A strategy of enquiry is constructed providing a framework for the design and execution of the research.

5.1 Research Justification and Intended Contribution to Knowledge

The former chapters of this thesis have identified that there is a current gap when considering whether local energy policies which promote the adoption of HN and CHP in new residential developments have resulted in the anticipated reductions of CO_2 in practice.

The evaluation of policy research has established that local planning control is one of the primary tools available to local authorities to drive policy agendas. Consequently, local planning is taking on an influential role in design to secure a low energy commitment from developers. An integral part of planning is demonstrating compliance with local energy polices including those that promote the feasibility assessment of HN and CHP. Energy policies such as the Merton Rule and TLP have been successful by increasing the uptake of HN, CHP and other RE technologies. However, it has been argued that the generality of these policies can ignore the contextual factors that shape the energy use of a specific building, development or site. Contact between the technical actors and stakeholders who will ultimately implement the chosen technologies in practice has been discouraged by policy. While monitoring reports consistently conclude that TLP policies will result in CO_2 reductions from new residential developments, a gap exists in empirical evidence to support these claims.

The existing research suggests that early decisions in a project have a significant impact on the energy performance of a building once in operation. Furthermore, the actors involved can often lack the relevant expertise to appropriately evaluate the decisions being taken. It has also been suggested that regulatory pressure can lead to over-optimistic expectations of achievable CO_2 reductions. The way these factors relate to each other and their impact on:

the quality of feasibility assessments being undertaken; the resulting decisions to select, in this instance HN-CHP, over other technologies; and the resulting implication for the EPG, is an area currently missing from the existing academic field.

Although the theme of this research could apply to other RE technologies, HN and CHP are currently heavily promoted within design guidance and energy policy. Previous examination of energy policy has suggested that HN-CHP is a major contributor to the reduction of CO_2 and the future of integration of RE technologies. It has been demonstrated through the examination of the available research that HN-CHP systems exist in a complex spatial, economic and technical context. Therefore, early decisions are highly influential to performance in practice. Examination of existing research related to building performance has shown that there is limited data regarding the EPG of residential HN-CHP systems from design intent to performance in practice. The secondary data available from industry POE has suggested high DHL consumption can result in a significant increase in energy and associated CO_2. Empirical evidence is therefore required to examine the performance of HN-CHP in a residential building.

Throughout the examination of existing research, the emphasis of feedback and actionable knowledge has been consistent. In terms of planning policy, feedback is a key requirement to provide evidence-based policy. Design feedback identifies performance in practice, whether there are failures or successes, in order to inform future designs. Finally, lack of feedback is also cited as one of the contributing factors to the EPG. This research will provide empirical evidence which will contribute to the feedback cycle in each of these research fields.

5.2 Research Questions

The connection and unique aspect of this research is the current lack of existing knowledge regarding the performance in practice of HN-CHP and how the decisions taken at the local planning stage contribute to the EPG. This has led to the formation of the primary research question:

Are the local energy policies that promote the adoption and implementation of Heat Networks and CHP technologies in small scale residential buildings leading to the anticipated reductions in energy and CO_2 emissions and, if not, what are the reasons?

Secondary questions are posed that direct the research and maintain the focus within the research theme:

Secondary Questions:

1. *How do local energy policies influence the selection of low and zero carbon technologies?*
2. *What are the motives for the adoption of a Heat Network and CHP in a new residential development?*
3. *Do local energy policies promote appropriate feasibility assessment of Heat Networks and CHP?*
4. *What scale of energy performance gap can be found in small residential Heat Networks and CHP systems?*

5.3 Research Design

The purpose of the research design is to determine a logical framework in the selection of research methods for collecting evidence. Taking a logic based approach ensures that the evidence collected will draw unambiguous conclusions. Arksey, Baldry, Sarsahar, and Newton (2002) identify the challenges of completing research in the field of construction and the built environment where many different subjects and disciplines are all contained, for example, natural sciences, social sciences, engineering and management. Research studies in the field of construction and the built environment have been criticized for their anecdotal approach when investigating 'real world' phenomena. Therefore, a clear definition of a research strategy is a fundamental requirement to achieve a sound empirical study of the built environment (Amaratunga et al, 2002).

The interactions of case study as part of a mixed methods approach is considered appropriate for the context of this research. This type of case study research has precedent within the evaluation of energy performance of buildings. For example Jones, Fuertes and De Wilde (2016) conducted a case study across six identical new build dwellings to determine the gap between simulated and measured energy performance. Nooraei, Littlewood and Evans (2013) used semi-structured interviews and spot temperature measurements to gain feedback on occupants' thermal comfort in a case study building. Birchall (2011) used measured energy data, occupant surveys, focus groups, and observations to appraise the performance of a low energy office building.

The practice of Post-Occupancy Evaluation (POE) of buildings requires the use of both qualitative and quantitative methods to gain a sufficient range of data required to complete the evaluation. Bordass (2004) explained that there are four principal kinds of feedback in POE: observations, questionnaires or interviews, facilitated discussions, and quantitative data (e.g. monitoring, testing, performance statistics). Brown (2015) used qualitative questionnaires to produce data on occupant's experiences in four new residential tower buildings. This research seeks to establish if a quantifiable EPG exists in residential developments with HN-CHP. This is investigated through quantitative data (meter readings, energy calculations). The potential influences of local energy policy for this EPG are established through the investigation of qualitative data (documents analysis, observations, questionnaires). A mixed methods approach is fundamental to answering the research question.

5.3.1 Research Paradigm

Part of the research design resides within the context of a theoretical perspective (philosophical stance), that Creswell (2003) suggests are 'Knowledge Claims'. These claims act to guide the assumptions the researcher will form about how and what they learn during the research. Table 5.1 provides four paradigms with their major elements of each position.

Table 5.1: Alternative Knowledge Claims Positions (Creswell, 2003)

Postpositivism (Quantitative / Deductive)	**Constructivism (Quantitative / Inductive)**
Determination Reductionism Empirical observation and measurement	Understanding Multiple participant meanings Social and historical construction Theory generation
Advocacy / Participatory	**Pragmatism**
Political Empowerment issue-orientated Collaborative Change-orientated	Consequences of actions Problem-centred Pluralistic Real-world practice orientated

The perspective of professional practice is key to the investigation and gives an insider researcher position to understanding the influence of energy policy and ES decisions on the EPG. The research will therefore be conducted in the real world view of the consequences of actions in professional practice. It also puts the exploration of human knowledge and activities at the core of the research question, leading to a pragmatism paradigm centred on the consequences of actions and real world practice (Creswell, 2009; Rylander, 2012).

Creswell (2003, p.11) identifies that pragmatism places the research problem at the centre of the study and '*applies all approaches to understanding the problem*'. Pragmatism is therefore primarily focusing on the '*what'* and '*how'* of the problem with data collection and analysis methods are chosen from 'what works', selecting those that provide the most insight into the research question (Patton, 1990; Teddlie and Tashakkori, 2009). A pragmatist researcher is therefore free to choose liberally from both quantitative and qualitative methods and assumptions (Creswell, 2003, p.12).

5.3.2 Mixed Methods Research

The term 'mixed-methods' or 'multi-strategy' are used by Creswell (2003) and Bryman (2004) to describe collecting and analysing both quantitative and qualitative forms of data in a single research design. Rossman and Wilson (1991), and Greene et al (1989) identify similar purposes for applying mixed methods research over mono research methodologies (table 5.1). Gray, (2013) explains that because a mixed method approach allows simultaneous generalisation of data, the researcher gains a deeper contextual understanding of the research phenomenon.

Mixed methods, like all research approaches, need to be reviewed through a theoretical lens (Mackenzie and Knipe, 2006). An appropriate research paradigm is therefore required for this research and is further discussed to investigate the research approach.

Table 5.2: The Purpose of Mixed Methods Research (Creswell, 2003)

Purpose	**Description**
Triangulation	Convergence and corroboration of results from different methods
Complementary	Enhancement and clarification from the use of both deductive and inductive results
Development	Using results from one method to develop and inform results from another method.
Initiation	Discovering new perspectives and allowing questions and results to be recast from one method to another
Expansion	Extend the breadth and range of research by using facets of inquiry from both deductive and inductive approaches.

To answer the research questions both confirmation (deductive) and exploratory (inductive) approaches will be required. For instance, the determination of the scale of EPG (deductive), and exploring the influence of energy policy on the EPG (inductive). Typically, only deductive or inductive can be applied to a single research strategy. However, Grey (2013) explains these processes are not mutually exclusive, both can occur within a single research project. Teddlie et al (2009) also define this as a major advantage of mixed methods: "*it enables the researcher to simultaneously ask confirmatory and exploratory questions in the same study*". Amaratunga et al (2002) provides a list of benefits (table 5.3) that ensure the research design maximises the strengths of mixed method approach when applied in the field of construction and build environment. Fellows and Lui, (1997) illustration, adapted in figure 5.1, identifies how simultaneous use of methods is very powerful for gaining insights and results, and for making inferences and in drawing conclusions (Amaratunga et al, 2002).

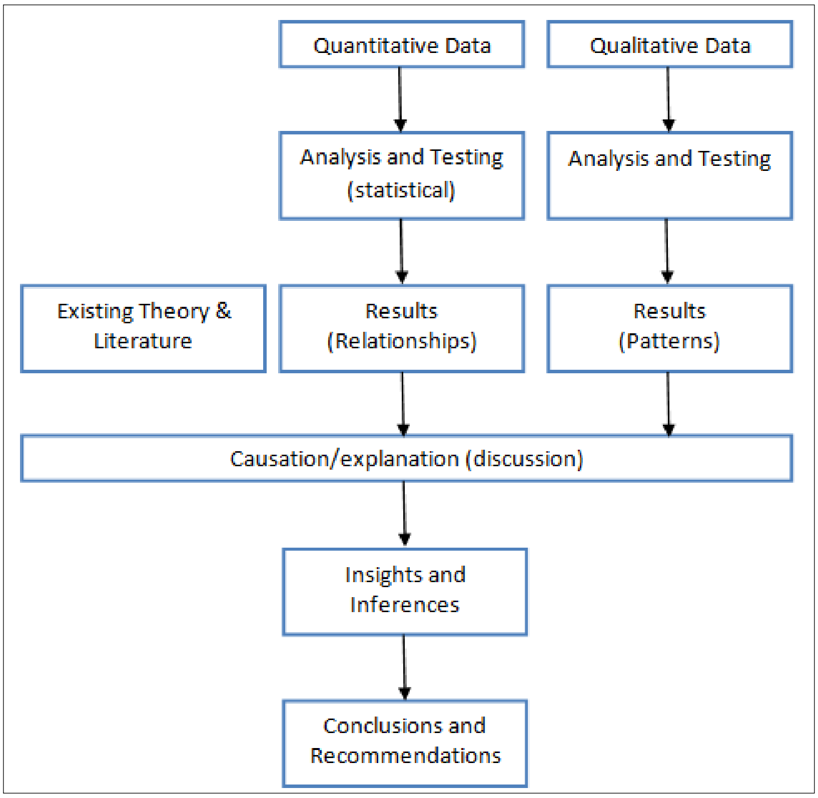


Figure 5. 1: The Use of Multiple Data Types in Mixed Methods (adapted from Amaratunga et al, 2002)

Table 5.3: The Strengths of Mixed Methods in Construction Research (adapted from Amaratunga et al, 2002)

Method	**Benefits to research**
Qualitative	Qualitative methods, especially observation or interviews, allow the researcher to develop an overall "picture" of the investigation.
Qualitative	Construction and built environment research involves behavioural aspects, this qualitative understanding is appropriate to investigate from the informants' point of view.
Qualitative	Much of construction and built environment research is still largely exploratory. Qualitative method allows for unexpected development that may arise from the research.
Quantitative	Analysis of date may complement findings from qualitative methods by indicating their extent.
Quantitative	Analysis of data may confirm or reject any apparently significant data and the relationships that may emerge from the research.
Quantitative	Quantitative methods can be used to enable statistical testing of the strengths of such relationships.
Quantitative	If such relationships are determined, then quantitative methods are weaker in providing explanations, whereas qualitative methods may assist in understanding the underlying explanation of significance.

Creswell (2003) explains that there are two general strategies to mixed method approach: sequential and concurrent (table 5.4). Grey (2013) explains that a case study is unlikely to occur in a sequential process. In a case study, the evidence is collected and analysed. If the discovered concepts are used to inform the collection and analysis of the proceeding case study, it is difficult to draw inferences from the results as the researcher will not be comparing 'like for like' (Grey, 2013). Adopting a concurrent procedure to a mixed methods approach allows 'converging of evidence' through triangulation of data (Grey, 2013).

Table 5.4: Strategies for Applying Mixed Methods (adapted from Creswell, 2003)

Mixed Method Strategies	
Sequential procedures	The elaboration of findings found in one method by applying another method. This may involve beginning with a qualitative method for exploratory purposes and following up with a quantitative method with a large sample so that the researcher can generalise.
Concurrent procedures	Data is collected from both methods at the same time and the researcher converges the multiple-data to provide comprehensive analysis of the research problem.
Transformative procedures	Research is conducted through a theoretical lens that frames the topics of interest, collection methods and outcomes. This lens influences the collection method which could be either sequential or concurrent.

5.3.3 Strategy of Inquiry

This research follows a pragmatic inductive-deductive approach. The knowledge claims arise from the actions, situations and relationships that exist within the boundaries of the research questions. This type of research is synonymous with pragmatism. A working theory has been formulated through the existing academic and industry literature (inductive). Through a deductive process, empirical data is gathered to deduce any patterns and relationships that emerge and lead to the conformation, refutation or modification of the initial theory. Figure 5.2 provides the framework of the strategy of inquiry.

Data will be collected through two concurrent workstreams: a survey of industry professionals and POE of a case study. The research strategy is designed to gain an independent perspective from the professionals directly involved in the planning, design and construction of HN-CHP in new residential developments. Through triangulation of the qualitative and quantitative data the findings will be confirmed through convergence of different perspectives to improve reliability and the generalisation of findings.

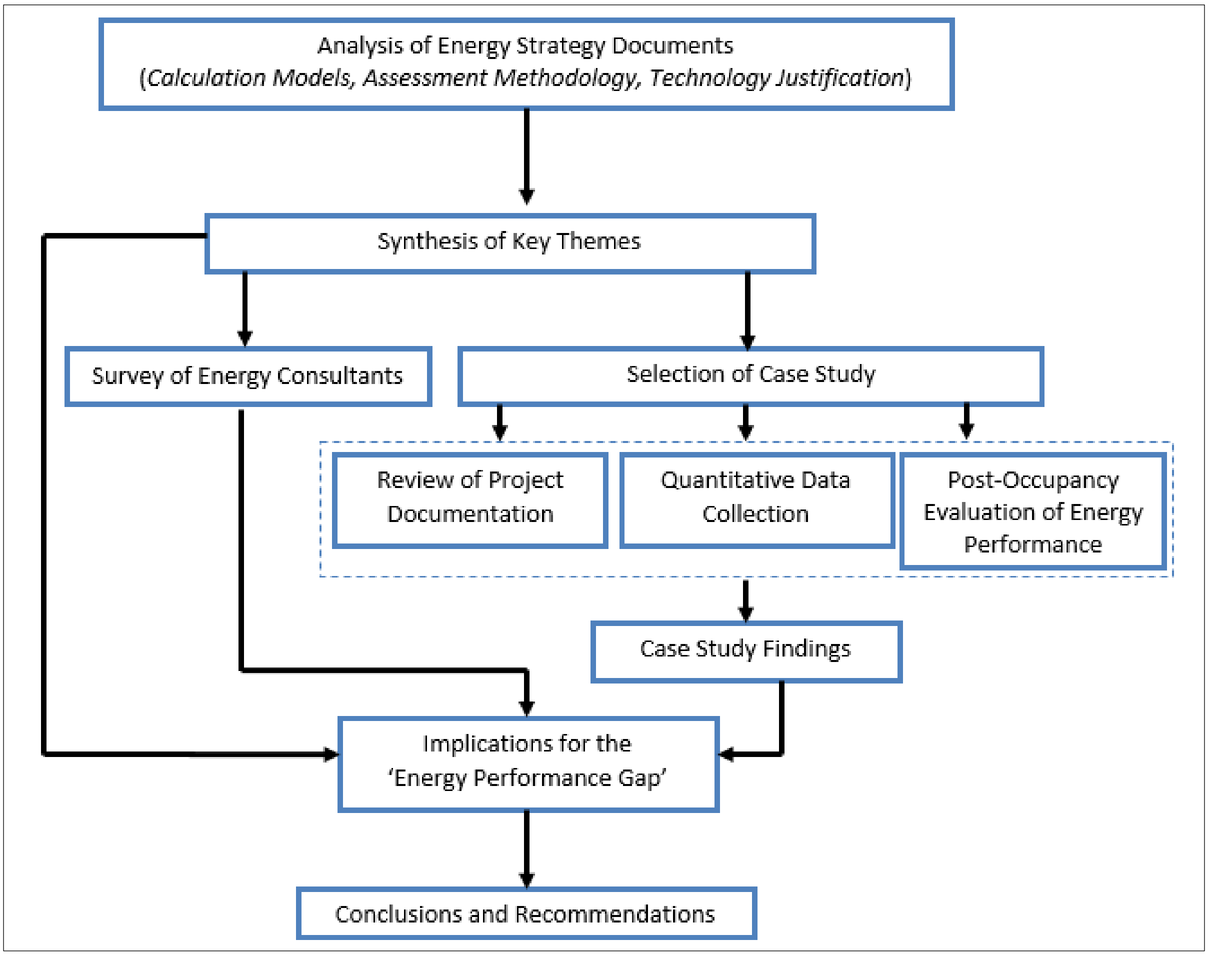


Figure 5.2: Research Design Strategy of Inquiry

5.3.4 Limitations and Boundary

Gray (2011) suggests that explicit boundaries of the research should be set to limit the scope of the research:

<u>Inside research boundary:</u>

- The London Plan policy directly related to the reduction of residential CO_2 emissions and the adoption of HN-CHP.
- The energy performance of small scale heat networks with combined heat and power.
- The assessment of CO_2 emissions for new residential developments.
- The technical and economic feasibility assessment of HN-CHP.

Outside Research Boundary:

- The London Plan policy not directly related to the reduction of residential CO_2 emissions and the adoption of HN-CHP.
- Social implications of technology selected. For example: fuel poverty, aesthetics, overheating, air quality, noise.
- Embodied CO_2 emissions.
- The GLA's long term strategic strategy for decentralised energy in London.
- Complexities of project delivery. For example: financial, programme, political influence, etc.
- The technical design or installation quality of heat networks with combined heat and power
- Medium or Large scale heat networks.
- Exergy of the HN-CHP system.
- Thermal warming of the building mass resulting from HN's distribution heat loss

5.3.5 Triangulation

Triangulation is a method of collecting data through different data gathering techniques which converge upon particular findings. By corroboration of findings across multiple data sets, the potential biases from a single method or by the investigator are mitigated (Bowen, 2009).

Triangulation is undertaken in this research project by comparing the ES document content analysis, case study POE and industry survey (figure 5.3). Combining these research methods and their data collection techniques adds: depth, reliability and validity to the research findings. This enables accurate conclusions and recommendations to be drawn.

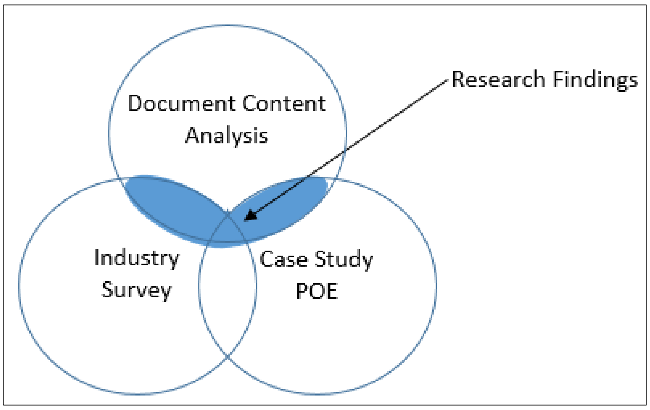


Figure 5.3: Triangulation of Research Findings

5.4 Chapter Reflectance

This chapter has identified the existing gap in knowledge relating to the EPG in residential buildings. Primary and secondary research questions have be defined. This chapter has explored and presented a research design within the theoretical perspective of pragmatism. A strategy of inquiry has been presented to guide the research to enable data to be collected and conclusions to be drawn with appropriate rigour and validity.

CHAPTER 6: EXAMINATION AND ANALYSIS OF ENERGY STRTAGEY DOCUMENTS

This chapter will provide a systematic analysis of the professional energy strategy documents submitted in real world planning applications for new residential buildings. A method is presented and used for the selection, analysing and identification of themes within the documents collated. A reflection on the findings and their relevance is presented.

6.1 Document Analysis Method

An ES is a mandatory document of a planning application in London and is available publicly to all stakeholders of a planning application. It defines to planning officers how the policy and SPG guidance have been adopted in order to secure a reduction in a development's CO_2. The GLA use ES documents as evidence to evaluate the effectiveness of planning policy and to justify further revisions to policy. These ES documents therefore contain important data regarding how energy policy has been applied in practice; the designer's evaluation of different energy saving measures (including HN-CHP); and the motives that inform their decisions. An analysis method is therefore required in order to systematically evaluate the documents. Day et al (2009) formed a database of pre-set data before analysing in a spreadsheet form.

Bowen (2009) explains that organizational and institutional documents have been commonly used in research for years and that document analysis provides a systematic procedure for eliciting meaning, gaining understanding and developing empirical knowledge. The analytic procedure requires the finding, selecting, appraising and synthesizing of the data into themes and categories (Bowen, 2009; Grey, 2013).

Bowen (2009) describes five ways of how document analysis can serve research. Table 6.1 describes how this research will be served by the use of document analysis. Atkinson and Coffey (1997, 2004) advise that a researcher should carefully consider how document analysis serves their research. Insufficient detail, low availability and bias in document selection can be disadvantages of the use of document analysis in research (Bowen, 2009). Table 6.2 describes these disadvantages, how they may impact this research and actions that will be taken so they are avoided.

Table 6.1: The Use of Document Analysis (adapted from Bowen, 2009)

How Document Analysis Serves Research	**Application to this Research**
Data provides content to what is being investigated. Provides background and historical insight. Contextualize data from other research methods (e.g. interviews)	Provides the context to this research in relation to the creation of an Energy Strategy: style and format, economic and technical feasibility assessment of HN and CHP. Predictions of energy and CO_2 emissions reductions and data relating to the implications for the EPG.
Help identify relevant observations or questions that need to be considered/answered in the research.	A source of contract and data to provide themes for the case study investigation and survey.
Documents provide supplementary research data and add to knowledge base.	Data on how an Energy Strategy is conducted: assessment method, influences o decision making. Identification on the scale of developments that adopt HN and CHP.
A method of tracking changes and development.	Provide insight to how the method of evaluation and reasoning for technology selection has changed over time.
Verify findings or corroborate evidence from other sources	Results will be combined with findings from the case study and survey to triangulate findings.

Table 6.2: Disadvantages of the Document Analysis (adapted from Bowen, 2009)

Common Disadvantages	**Potential Impact on this Research**	**How Potential Impacts will be Avoided.**
Insufficient Detail: Documents are not produced specifically for the research and therefore will not provide sufficient detail to answer the research question.	An Energy Strategy document states how and what performance will be achieved. It does not state why the performance may not be achieved in practice.	The document analysis only forms one part of the data collection strategy, along with case study and survey data. Data from other methods will be available to help answer the research question. The document analysis is being used to deduce categories and themes that will help inform the analysis of the other data collection methods.
Low Retrieval: Documents are hard to find or access deliberately blocked.	Insufficient quantity of documents. Historic documents (>10 years) may have been removed from online databases.	Planning documents are made available through the LPA or GLA planning portal. The research focus is on applications related to the TLP timeframe (2004 onwards). It is therefore likely that sufficient documents will be available.
Biased Selectivity: Document author bias and researcher bias	The research must consider the subjectivity and any personal biases the author of the	A ‘criteria of selection’ (table 6.4) will be applied to the documents to ensure potential biases are removed.

	document may have.	

6.1.1 Analysis Method Applied

It is important for researchers to define the specific approach to content analysis they are going to use before analysing the data. By following an analytic procedure, trustworthiness and validity of the study is increased (Hsieh and Shannon, 2005).

Hsieh et al, (2005) describe three approaches to content analysis:

- *Conventional* (could also be described as 'grounded theory') – an inductive approach to analysis. The aim is to describe a phenomenon where existing data is limited. Categories flow from the data.
- *Direct* – can be either an inductive or deductive approach to analysis. Prior research may exist regarding a phenomenon, the aim is to validate or extend conceptually a framework or theory. Codes can be generated from the data or predetermined.
- *Summative* – a deductive or inductive approach. Identifying words or content within text, with the purpose of quantifying their use and then understanding its contextual use. Summative analysis goes beyond quantitative analysis by interpreting the content for underlying meaning.

Table 6.3 describes the difference in coding methods between the three approaches to content analysis.

Table 6.3: Major Coding Differences (Hsieh et al, 2005)

Type of Content Analysis	**Study Starts With**	**Timing of Defining Codes or Keywords**	**Sources of Codes or Keywords**
Conventional content analysis	Observation	Codes are defined during data analysis	Codes are derived from data.
Directed content analysis	Theory	Codes are defined before and during data analysis	Codes are derived from theory or relevant research findings
Summative content analysis	Keywords	Keywords are identified before and during data analysis	Keywords are derived from interest of researchers or review of literature.

The content analysis to be conducted in this research is of ES documents. As described in chapter 2, these documents are technical documents that use a pre-defined structure and content as defined by GLA guidance. The documents contain pre-defined procedures for the calculation of energy and CO_2 and technical appraisal of technologies based on published technical guidance and the author's technical expertise. Chapters 2 and 3 have examined and defined the structure, calculation methods and assessment of HN-CHP, which should be applied in these documents. Therefore, the keywords and content have been defined within the existing research literature. Chapter 4 has identified that an EPG exists within new residential developments. Key prescribed causes of the EPG include: poor early decisions in the design process, and inaccurate assessment (including modelling) of energy use. The purpose of the document analysis is to: understand the creative process of ES document within the real-world; how the energy policies are applied through the pre-defined structure and guidance; the technical assessment undertaken; understand the designer's interpretation of the assessment findings; and decisions taken in selecting HN-CHP as part of the proposed ES. This approach is therefore synonymous with *Summative* content analysis.

6.1.2 Criteria of Selection

Gray (2013) advises that a set of rules or *'Criteria of Selection'* must be established before the data can be analysed in order to ensure objectivity. Stemler (2001) warns that problems can occur if the assembled documents are incomplete in content, inappropriate for the analysis being undertaken, or hard to code because the content is ambiguous. Braun and Clarke (2006) argue that the collection of 'good' data is defined by a set of criteria; *what, why,* and *how* the data is collected. The study by Day et al (2009) identified similar issues with the analysis of ES documents, stating that documents were often incomplete or the data was not 'transparent' (p.2018). Where data were missing Day et al. made assumptions and used 'back-calculating' from stated CO_2 factors to complete their analysis (2009, p.2018).

While the documents selected will need to be appropriate to the research question being asked in order to obtain relevant data, they must also provide a representation of the real-world complexities of the phenomenon being examined. For instance, while the primary investigation of this research is the use of HN-CHP, documents will also need to be analysed that have omitted HN-CHP so an objective analysis can be drawn on the decisions for and against the adoption or exclusion of HN-CHP. Table 6.4 outlines the *'Criteria of Selection'* that will be applied to the gathered documents.

Table 6.4: Document Analysis Criteria of Selection (author, 2019)

Criteria of Selection	**Justification**	**Coding Method**
Document classed as an Energy Strategy.	These documents are a record of how the designers complied with the planning energy policy and the intended energy and CO_2 emissions performance of the development (see chapter 2).	0 = Reject 1 = Accepted
Document created after 2004	Energy policies were first introduced in the 2004 version of the London Plan (GLA, 2004).	Year as stated on the document. Documents with no dates will be rejected.
Document related to a development located within one of the 32 and City of London Boroughs	Boundary area of the research.	Planning Authority of the development. Documents outside the boundary area will be rejected.
Full Planning Application	An outline planning application may not have sufficient information regarding the site or the Energy Strategy.	Stated in the planning reference database.
Document is based on the London Plan Energy Policy.	The research is focused on the energy policy of the London Plan which promotes through the Energy Hierarchy the use of HN-CHP and has reported significant CO_2 emissions savings specifically from these technologies (see Chapter 2).	0 = Not Referenced 1 = Referenced
Document is related to a predominately residential development (>90% of useable floor area).	The research is focused on the application of HN-CHP in residential developments, therefore the residential element of the development must be responsible for the majority of energy and CO_2 emissions.	Review of domestic and non-domestic floor area (m^2).
Document is related to a 'small scale' <500 dwellings development	The research is focused on small-scale residential developments, where reports from the GLA have shown an increase in the uptake of HN-CHP (see chapter 2 and 3).	0 = Below 500 dwellings 1 = Above 500 dwellings

6.1.3 Coding

Coding is the process of organizing the data through the assignment of a symbolic word, short-phase or a symbol. Codes allow the data to be sorted and synthesized so they can be interpreted. Coding can be:

- *Pre-set* or a *priori* coding – derived from the literature, research problem, prior knowledge and expertise in the subject of the research.
- *Emergent Codes* – codes emerging directly from the reading and analysing of the data.

The two forms of coding can be used together in a 'hybrid' approach, beginning with pre-set codes and then adding to them as themes emerge from the analysis of the data (Stemler, 2001).

Content analysis has a common notion of simply providing a word-frequency count, with the assumption that the most frequent words reflect the greatest intent. However, Stemler (2001) argues that this can be misleading. Frequency counts should identify potential interests within the data and then the data should be viewed within its context, this procedure will help strengthen the validity of the inferences that are being drawn from the data (ibid, p.3). By this approach the data can become rich and meaningful through coding and categorisation.

Table 6.5 outlines the pre-set codes (i.e. keywords) that will be used through the analysis. The justification for their use is based on the existing research field (chapters 2 to 4), and finally the coding method applied to each document. A coding method based on numerical values has been applied. Numbers can be transformed easily into statistical and graphical representation of the data. Where the code is already a numerical value (e.g. a value of energy in kWh) the actual value is stated, represented by '*N'* in table 6.5. Every document was individual read and coded manually, results were entered into a spreadsheet for analysis.

Table 6.5: Document Analysis Pre-Set Coding Keywords and Content (author, 2019)

Keyword / Content	Justification	Coding Method
Energy Hierarchy	Defined in GLA policy as the method a designer must follow in forming an Energy Strategy.	0 = Not Referenced 1 = Referenced 2 = Referenced and followed
Energy Calculation Method	The GLA guidance defines the calculation that must be used. As established from the literature (chapter 4), the calculation tool used can influence the scale and type of the EPG.	1 = SAP 2002 2 = SAP 2005 3 = SAP 2012 4 = Dynamic Software 5 = Energy Benchmarks 6 = Other
HN was selected in the energy strategy	HN are one of the primary technical focus of the research.	0 = No 1 = Yes 2 = Not determinable (reject document)
CHP was selected in the energy strategy	CHP is the other technical focus of the research.	0 = No 1 = Yes 2 = Not determinable (reject document)
Heat Density (kWh/m^2)	As defined from the literature (chapter 3), heat density is a key factor in evaluating a HN design and energy performance.	0 = Not Referenced 1 = Referenced 2 = Referenced with verifiable data
Linear (Line) Heat Density (kWh/m)	As defined from the literature (chapter 3), line heat density is a key factor in evaluating a HN design and energy performance.	0 = Not Referenced 1 = Referenced 2 = Referenced with verifiable data
HN Distribution Losses	As established through the literature (chapter 4), DL have found to exceed design predictions.	0 = Not Referenced 1 = Referenced 2 = Referenced with verifiable data
Economic Assessment of HN	GLA guidance requires the economic assessment of a HN against individual gas boilers. The literature suggested (chapter 3) that HN-CHP selection should be based partly on an economic assessment.	0 = Not Referenced 1 = Referenced 2 = Referenced with verifiable data
Arguments stated FOR the inclusion of HN	As defined by the literature (chapter 4), early design decisions are considered a key cause of the EPG, therefore it is important to understand the designer's justification for the inclusion of a HN.	0 = Not Stated 1 = Stated
Arguments stated FOR the inclusion of CHP	As defined by the literature (chapter 4), early design decisions are considered a key cause of the EPG, therefore it is	0 = Not Stated 1 = Stated

	important to understand the designer's justification for the inclusion of a CHP.	
Arguments stated AGAINST the inclusion of HN	As defined by the literature (chapter 4), early design decisions are considered a key cause of the EPG, therefore it is important to understand the designer's justification for the inclusion of a HN.	0 = Not Stated 1 = Stated
Arguments stated AGINAST the inclusion of CHP	As defined by the literature (chapter 4), early design decisions are considered a key cause of the EPG, therefore it is important to understand the designer's justification for the inclusion of a CHP.	0 = Not Stated 1 = Stated

6.2 Findings and Key Themes

This section details the documents that were analysed and the results of the initial coding method. Pre-set themes and emergent themes that were identified have been coded, and statistical results are discussed.

6.2.1 Documents Analysed

A total of 50 documents were analysed, identified through the London Development Datastore (LDD)[12]. The LDD is a live database updated monthly that records planning consented developments. The LDD was filtered for developments that met the criteria of selection outlined in section 6.1.2. The LDD contains the planning reference, local planning authority and description of the development. The ES documents were downloaded from the local authority planning portal using the planning reference. The ES document related to the case study site examined in Chapter 7 was included in the analysis. Table 6.6 schedules the documents used in the analysis. The LDD contained 66,115 planning references. This was filtered based on criteria of selection for year, residential unit numbers and non-domestic area to 4,651 planning references. The sample of 50 documents were selected from this pool providing a cross range of development size, location and selected technology type.

The research could have benefitted from a larger sample of documents. However, the analysis of 50 documents was found to be sufficient to apply the coding method and to identify recurring themes across the documents. Day et al's (2009) study used a sample of 113 documents. However, their study analysed the documents for quantitative information

[12] London Development Datastore available at: https://data.london.gov.uk/dataset/planning-permissions-on-the-london-development-database--ldd- [accessed 03.06.2018]

only (selected LZC technology and CO_2 reduction), while this content analysis will also gather more detailed qualitative data. Furthermore, this research is using the document analysis as part of a wider strategy of inquiry. The evidence collected from the document analysis is triangulated with further evidence collected in chapters 7 and 8 to validate the research findings.

Table 6.6: Content Analysis Energy Strategy Documents

Ref No.	Document Year	Local Authority	No. Dwellings	Non-Domestic Area (m^2)	Energy System
1	2017	Islington	15	179.9	HN-CHP
2	2017	Barnet	33	-	Other
3	2017	Ealing	92	-	HN-CHP
4	2015	Haringey	69	1009	HN-CHP
5	2012	Barnet	25	-	HN
6	2009	Brent	115	310	HN-CHP
7	2013	Lewisham	29	-	HN-CHP
8	2011	Camden	54	-	HN-CHP
9	2016	Barking and Dagenham	55	-	Other
10	2011	Camden	37	-	HN-CHP
11	2015	Greenwich	124	-	HN
12	2011	Camden	12	-	Other
13	2010	Camden	52	-	HN-CHP
14	2014	Brent	128	240	HN
15	2007	Southwark	138	357	HN-CHP
16	2011	Hammersmith and Fulham	50	-	Other
17	2010	Islington	27	-	Other
18	2016	Haringey	88	-	HN
19	2009	Brent	335	702	HN-CHP
20	2011	Islington	65	-	HN
21	2011	Islington	6	-	Other
22	2017	Brent	149	-	HN-CHP
23	2015	Islington	21	-	Other
24	2016	Southwark	333	-	HN-CHP
25	2018	Croydon	55	711.1	HN-CHP
26	2013	Haringey	50	-	HN-CHP
27	2013	Brent	26	-	Other
28	2012	Ealing	89	-	Other
29	2016	Tower Hamlets	47	-	HN-CHP
30	2014	Haringey	52	-	HN-CHP
31	2016	Lambeth	12	-	HN
32	2015	Hackney	45	-	HN
33	2015	Croydon	42	-	HN-CHP
34	2014	Lewisham	60	-	Other
35	2011	Ealing	21	-	Other

36	2009	Tower Hamlets	121	110	HN
37	2017	Hackney	28	-	HN
38	2011	Brent	76	780	HN-CHP
39	2010	Barnet	309	1708	HN
40	2016	Haringey	69	614	HN
41	2016	Barnet	28	152	HN
42	2016	Barnet	60	-	HN
43	2016	Hackney	25	-	Other
44	2017	Wandsworth	29	574.6	Other
45	2016	Ealing	149	-	Other
46	2017	Greenwich	69	-	Other
47	2013	Barking and Dagenham	158	-	HN
48	2016	Lewisham	72	392	HN-CHP
49	2017	Greenwich	341	303	HN-CHP
50	2017	Brent	50	-	HN

6.2.2 Pre-set Themes - Coding Results

The codes (table 6.5) were applied through the 50 documents. The results were logged in a spreadsheet and the resulting data analysed. The results are represented here through statistical and geographical representation. The findings from the document analysis are discussed in relation to the research questions.

6.2.2.1 Energy Calculation Method

The London Plan requires that reductions in CO_2 are reported against a building regulations baseline design (GLA, 2006a; GLA, 2016). The SAP and SBEM assessments are the regulatory model for calculating new dwellings and non-domestic buildings CO_2 respectively. The earlier analysis of the existing research relating to EPG, identified that regulatory models do not take account of all of the consumed energy within a building or the variation in use and operation of the building. Some researchers argue that the EPG could be significantly reduced if the dynamic simulation was conducted (Van Dronkelaar et al, 2016).

The coding applied seeks to ascertain the most common calculation tool employed in the assessment the energy performance and CO_2 related to HN and CHP. It is expected that the SAP will be the most common tool, as this is the method prescribed by the GLA policy. However, the existing research and industry guidance identified that accurate assessment of energy demand is fundamental to the feasibility of HN and CHP. Furthermore, design energy modelling may differ significantly from regulatory models (CIBSE, 2015, p.20).

Figure 6.1 demonstrates that in the vast majority of the sample, (49 out of 50) the use of SAP assessments was the sole method applied. Only one document (ref no.6) utilised a secondary software, "*CHP sizer (version 2) distributed by the Carbon Trust*", to carry out a "*preliminary evaluation of the feasibility of CHP*" (6[HN-CHP]). No other tools were referenced.

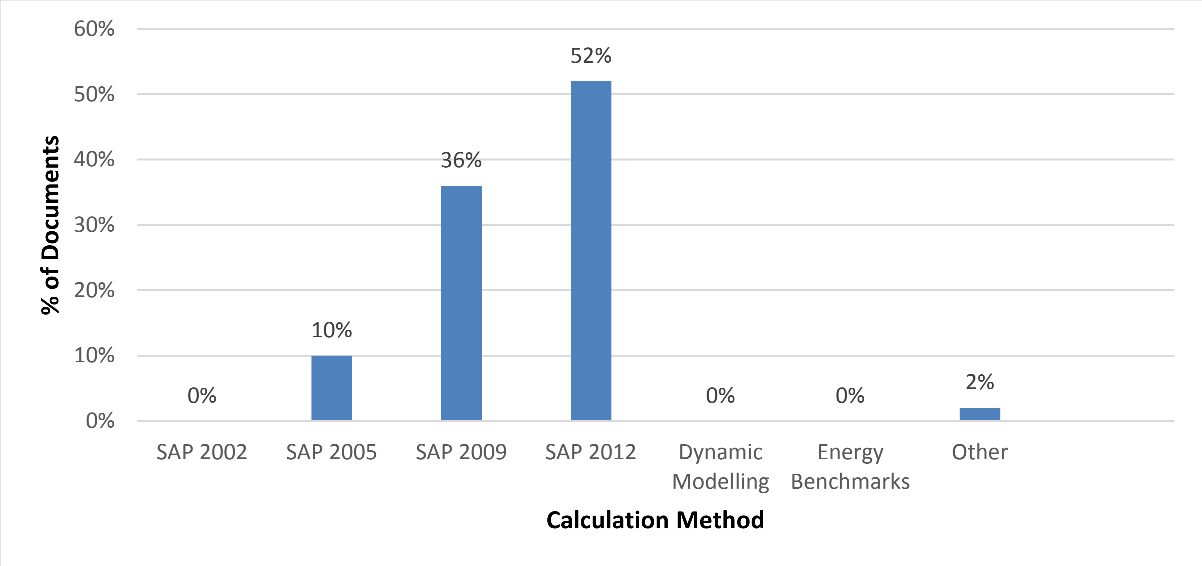


Figure 6.1: Coding Results – Energy Calculation Method Used

SAP was the main energy model tool used in the assessment of energy and CO_2. Although regulatory models were anticipated to be the predominant assessment tool due to their specific expression in the policy, the significant finding is that no other secondary tool is used to validate the regulatory assessment. This result is important as the regulatory tools are not accurate models, and are implicated as one of the primary causes of the EPG (see; Carbon Trust, 2011; Menezes et al, 2012; De Wilde et al, 2014; Van Dronkelaar et al, 2016).

This finding provides an indication of the influence that prescriptive policy has on the energy calculation tool employed by designers in the feasibility assessment of HN-CHP. The accurate assessment of energy demand is fundamental to the feasibility assessment of HN-CHP (Carbon Trust, 2004; CIBSE, 2013; CIBSE, 2015), but the findings from the coding show that simple models are being employed by designers over more accurate complex (dynamic or performance) models. This phenomenon is supported by Williamson (2012) who identified that simple calculations tools are more likely to be used over more complex design specific modelling software, as these tools are required to comply with building regulations, building control and other performance standards. The analysis suggests a practice of designing for compliance rather than technical performance.

6.2.2.2 HN and CHP Assessment Measures

Key factors that designers should consider when evaluating HN and CHP were identified (chapter 3). These factors are relevant to this research as the examination of the policy guidance found that GLA requires that an ES provide a viability assessment (economic) as well as a feasibility (engineering and practical constraints) as part of the HN and CHP assessment (GLA, 2013a P.66).

HD and LHD are recognised as the critical energy demand characteristics of a development. These characteristics are used to determine the technical efficiency and economic viability of a HN. The policy guidance documents and academic literature examined earlier stated that HD is important for the feasibility of HN, as lower density developments result in higher capital cost and DHL. Furthermore, a correlation has been shown between LHD and DHL (see figure 3.5), indicating that lower LHD increases DHL which is a contributing factor to low efficiency and uneconomic viability. Economic viability is as critical as technical viability in the assessment of CHP for residential buildings. To optimize economic viability, as this thesis has emphasised, CHP capacity should be closely matched to the building's heat and electrical power loads.

A coding value was applied to each of the identified key factors (table 6.7). The documents were analysed to identify if the key factors formed part of the feasibility assessment. The coding analysed for both descriptive references of these factors, and secondly if verifiable data had been provided in justification.

It is recognised that this coding process is based on the identification of exact terminology. In the case of 'heat density', this can be expressed in multiple ways (e.g. heat demand, hot water demand) or be closely related to other forms of density (i.e. dwelling numbers, m^2 of heated floor area, population, etc.). These instances would therefore not appear within this coding method as they do not match the coding terminology. The next section of this chapter (6.2.3) analysed the arguments (for and against) relating to the selection of HN and CHP. One of the categories established through this analysis identified the various terminology and forms of density that could be grouped into a single theme. This and the other emergent themes are discussed in more detail later in this chapter. This section is solely focused on the coding of the key factors as defined in table 6.7.

Table 6.7: Coding of Key Factors

Key Factor	**Coding Value**
Heat Density *The amount of thermal energy required to meet all heating demand in the development.*	0 = Not Referenced – *no statement or data given*. 1 = Referenced – *a statement was made relating to the factor.* 2 = Referenced with verifiable data - *a statement was made relating to the factor and included calculated data*.
Linear (Line) Heat Density *The amount of thermal energy required to meet the heating demand per meter of distribution pipework.*	0 = Not Referenced 1 = Referenced 2 = Referenced with verifiable data
Economic Assessment *A comparison of financial implications of HN against one or more alternative technologies.*	0 = Not Referenced 1 = Referenced 2 = Referenced with verifiable data
Heat Demand Profiles *A profile of changes in thermal demand over a defined period (monthly, 24 hours)*	0 = Not Referenced 2 = Referenced with verifiable data
Electrical Demand Profiles *A profile of changes in electrical demand over a defined period (monthly, 24 hours)*	0 = Not Referenced 2 = Referenced with verifiable data

Figure 6.2 present the results of the coding analysis. There were very few references to any of the key factors and no verifiable data was stated for HD or LHD. Only one document presented an economic assessment. The results also demonstrate that two thirds (66%) of the sample documents did not reference any one of the key factors.

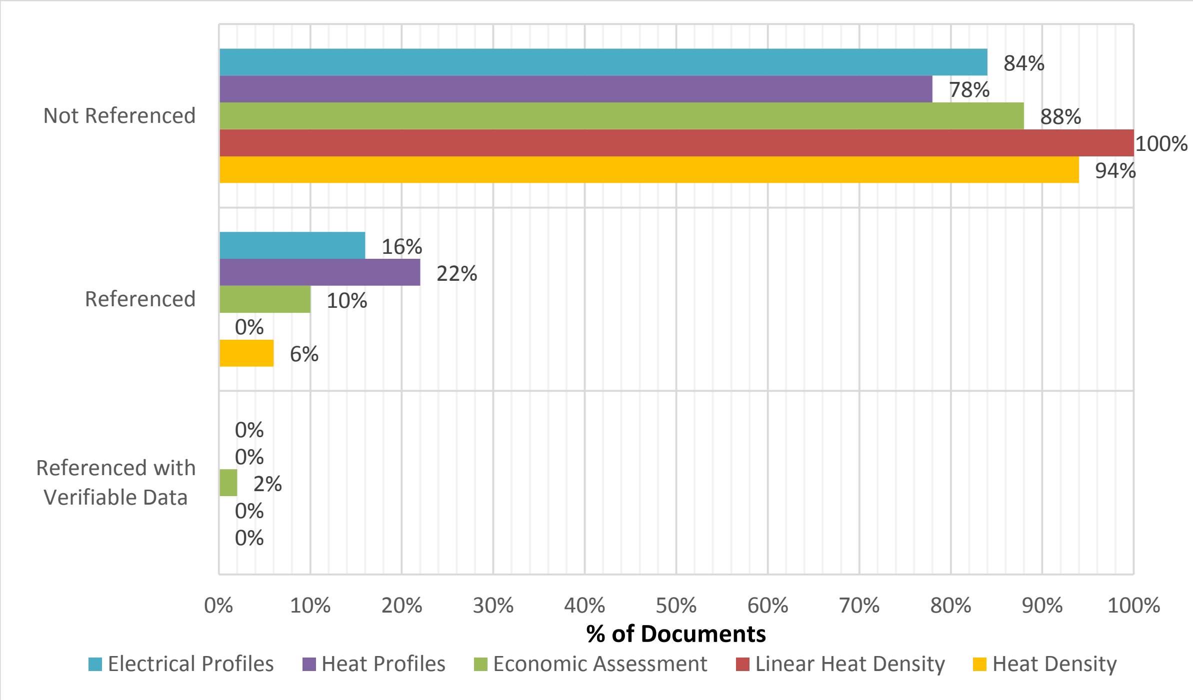


Figure 6.2: Coding Analysis Results for Heat Density, Linear Heat Density, Economic Assessment and Profiles

The GLA policy guidance examined in chapter 2 requires the technical and economic assessment of HN and CHP, without defining a specific method of how this should be undertaken by designers. The coding results are significant for this research as it has been found that almost none of the key factors prescribed by industry guidance and academic studies is being routinely used by designers. In the absence of a defined method by the GLA or the adoption of academic or industry methods, it is currently unknown by what method designers are undertaking the essential technical and economic assessments of HN and CHP. Furthermore, without verifiable data it is unknown how the claims by the designer that the adoption or exclusion of HN and CHP is the most technical and economic advantageous energy systems for a development. The next section of this chapter (6.2.3) analyses the arguments stated by the designer relating to the selection of HN and CHP. Part of this analysis will examine the resulting themes to identify if a method or methods can be identified.

6.2.2.3 Assessment of Distribution Heat Losses and Auxiliary Energy Consumption

The examined literature has shown that HN energy inputs (DHL and AE) should be included within a feasibility analysis (CIBSE, 2013; 2015; Xing et al, 2012). Although these two factors are inherently calculated in the SAP, for DHL it is clear that the assumed figures are routinely exceeded in practice and AE consumption can vary significantly. A coding value was applied to DHL and AE energy consumption (table 6.8). The sample documents were analysed to identify if each of these formed part of the feasibility assessment. The coding analysed for both descriptive references and secondly if verifiable data had been provided.

Table 6.8: Coding of Distribution Heat Loss and Auxiliary Energy Consumption

Key Factor	**Coding Value**
HN Distribution Heat Losses *The different between thermal energy generated and thermal energy consumed.*	0 = Not Referenced – *no statement or data given.* 1 = Referenced – *a statement was made relating to the factor.* 2 = Referenced with verifiable data - *a statement was made relating to the factor and included calculated data*.
Auxiliary Electrical Energy *The amount of electrical energy consumed in distributing heat.*	0 = Not Referenced. 1 = Referenced. 2 = Referenced with verifiable data.

The results show that there were few references to DHL or AE consumption within the documents sampled (figure 6.3). Furthermore, no verifiable data was stated for either in any of the sample documents. The AE was only referenced in 8% of the sample documents (figure 6.3).

Figure 6.3: Coding Analysis Results for Distribution Heat Loss and Auxiliary Energy

Of the schemes that adopted a HN (70%), the coding results show that the majority (77%) did not make any reference to DHL as part of the feasibility assessment. However, examining the year the documents were published does show an increase in the proportion of documents that referenced DHL. Documents dated between 2011 and 2015 (22 documents) 18% made reference to DHL, whereas documents dated between 2016 and 2018 (21 documents) 43% referenced DHL. A larger sample of documents would be required to derive any definitive conclusions from these results, however, a basic inference could relate to the growing availability of guidance documentation (GLA, 2016 & CIBSE, 2015) and research being conducted that consider the significant energy related to DHL.

The coding results are significant for this research as it has revealed that two factors that are fundamental to the assessment of energy consumption and thus CO_2 are not being routinely discussed. It is recognised that the ES based on the SAP will calculate the energy and CO_2 related to these two factors as part of the inherent methodology. However, research has shown that these calculations underestimate the energy consumption in practice (BRE, 2016 & ade, 2017). The limited recognition of these factors within the documents may undermine the feasible performance of HN in practice, if those implementing the ES are not aware of these critical performance factors. Consequently, an inefficient HN may not be able to reduce CO_2 compared to individual energy systems despite a CHP (or other LZC) providing the source of heat.

6.2.3 Analysis of the Designer's Arguments for Adopting a Heat Network and CHP

The next part of the document analysis was to identify and categorize into themes the justifications given by the designer's regarding the decision to either adopt or discount HN and CHP. By examining the arguments presented themes can be formed that describe the prominent motives and influences related to the selection of HN and CHP. The synthesis of the designer's arguments within the ES context will help strengthen the validity of the inferences drawn from this document analysis and provide empirical data that answers the research questions (Stemler 2001, p.3).

6.2.3.1 Document Analysis Emergent Themes

The sample documents were analysed for all sentences or phrases that could be identified as a motive, influence or justification related to the decision to either adopt or discount a HN and CHP. The extracts of the documents were organised into common categories, then placed systematically under distinct themes in order to group similar categories and reduce the overall number of themes. This meant common themes could be more easily identified across the document sample. The themes were then coded to provide a statistical and graphical representation of the data. This analysis identified the number of sample documents that referred to a theme at least once in their assessment of both a HN and/or CHP. A single document may have made multiple references to a single theme, however, these were only counted once. The purpose of this part of the analysis is synthesize common themes from the sample of 50 documents, therefore the relevant analysis is the number of documents referencing to the same theme not the frequency that those themes occur. Figures 6.4 and 6.9 demonstrate the proportion of each theme referenced for HN and CHP respectively.

Table 6.9: Themes and Categories Derived from Sample Document Analysis

Theme	**Categories**	**Proportion of Total Themes Referenced (%)**
Air Quality	Exhaust Emissions Air Quality	0.5%
Building Design	Space constraints Building Layout	5.3%
CO_2 Emissions	CO_2 Emissions Reductions CO_2 Emissions Increases	12.0%
Case Study	Referring to a Case Studies Mature Technology In-use Performance	2.4%
Choice of Energy Supplier	Choice of Energy Supplier	1.0%
Distribution Loss	Pipework Heat Losses Overheating of Internal Areas	20.7%
Economic	Capital Cost Operational Cost Economic Evaluation Grants Fuel Bills	5.8%
Efficiency	Thermal Efficiency Electrical Efficiency	16.3%
Electrical Density	Electrical Demand Electrical Base load	11.5%
Future Proof	Connection to local DHN Install of LZC Technologies Fuel Flexibility	2.4%
Density	Heat Demand Summer Heat Base Load Site Density Site Size	10.1%
Noise	Noise	10.6%
Security of Supply	Loss of heating and hot water	0.5%
Planning Policy	National, Regional and Local Policy Guidance Documents	1.0%

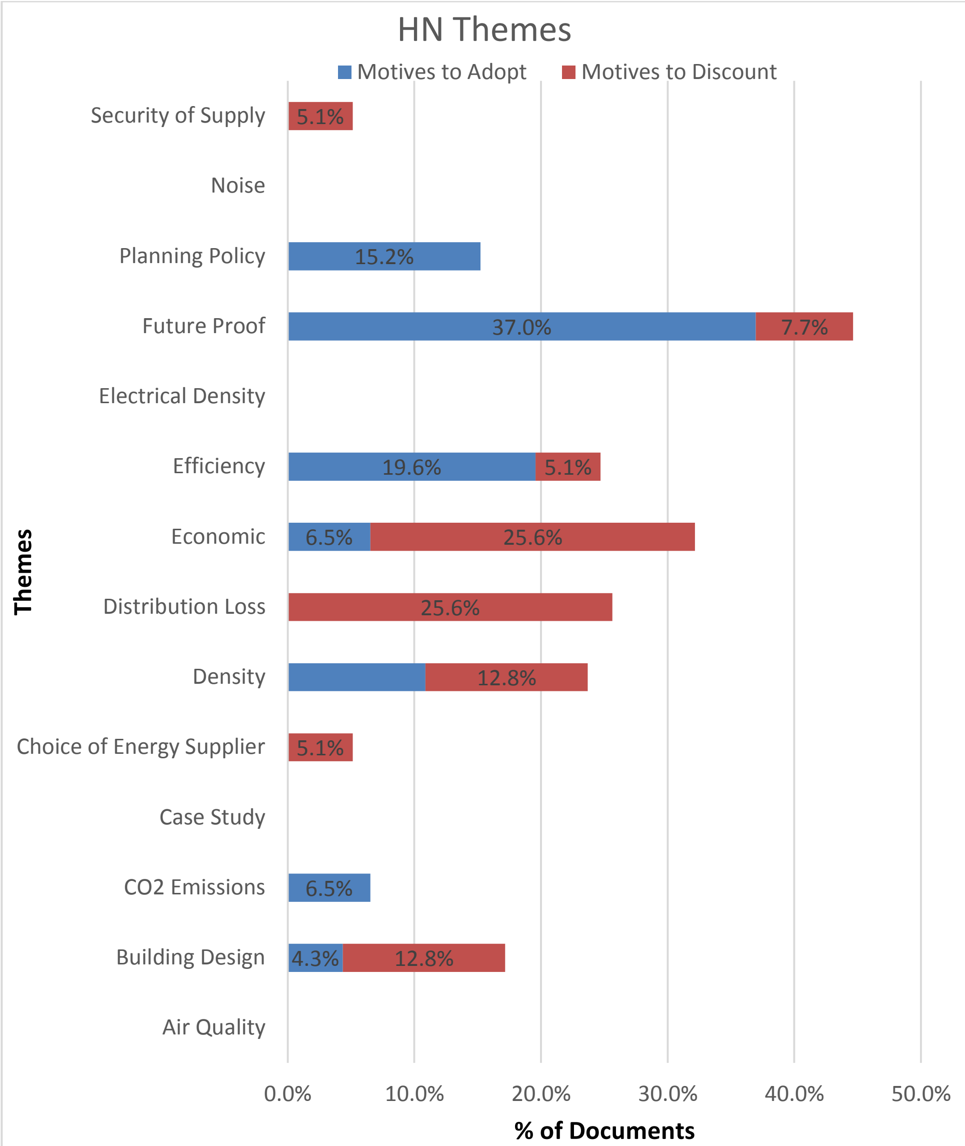


Figure 6.4: Heat Network – Coding Results of Themes and Categories

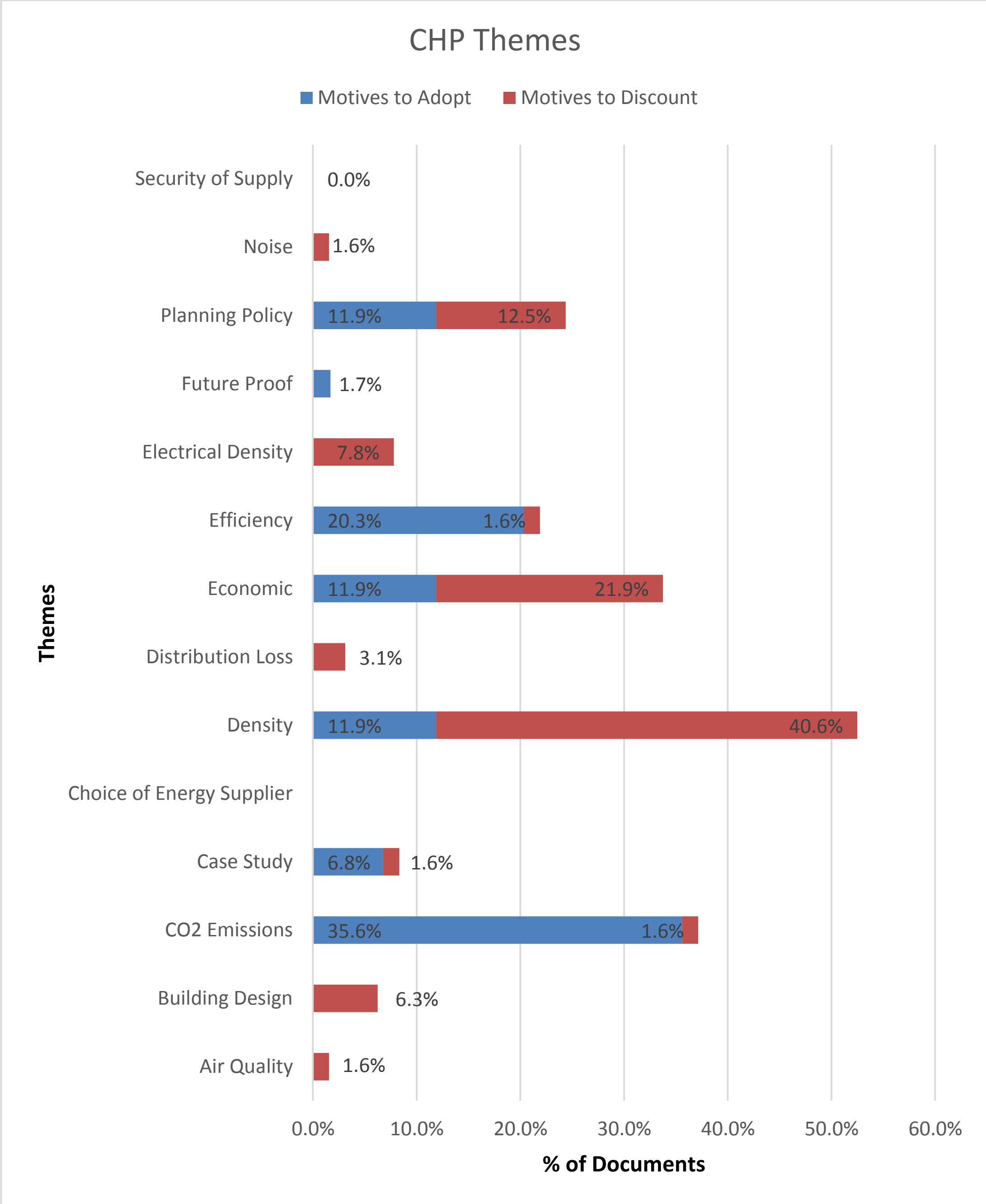


Figure 6.5: CHP – Coding Results of Themes and Categories

A total 14 distinct themes identified in the sample (table 6.9). Eight were identified to have been applied in both the assessment of HN and CHP. The remaining six themes were only found in relation to one assessment, either HN or CHP. The results identified that there were a greater number of themes related to the assessment of CHP (58.8%) than HN (41.2%).

Figure 6.7 identifies that the primary themes across the whole sample were *Heat Density* (20.7%), *Economic* (16.3%), *CO_2 emissions* (12%) and *Efficiency* (11.5%). However, considering figures 6.4 and 6.5 these themes are not represented as the primary themes when considering HN and CHP separately. Figure 6.4 demonstrates that the primary themes for the assessment of a HN were; *Future Proofing, Economic, Distribution Loss and Efficiency*. Whereas the primary themes related to the assessment of CHP (figure 6.5) were: H*eat Density, CO_2 emissions, Economic, and Planning Policy*. The identification of primary themes indicates that although there is some commonality, designers considered different themes during the assessment of a HN compared to a CHP.

There is variation among the themes that were applied by designers as a *motive to adopt* or a *motive to discount* a HN or CHP respectively. Only the theme of Efficiency was identified as a common prominent theme for both HN (19.6%) and CHP (20.3%), in total representing over 19% of the sample as a *motive to adopt*. The same theme was used as a *motive to discount* 5% (HN) and 1.6% (CHP). There were otherwise clear differences among the themes for each.

For a HN the most prominent themes as a *motive to adopt* were: *Future Proof* (37%), *Efficiency* (19.6%), *Planning Policy* (15.2%) and *Heat Density* (10.9%). Whereas the most prominent theme for as a *motive to discount* were: *Distribution Loss* (25.6%), *Economic* (25.6%), *Building Design* (12.5%) and *Heat Density* (12.5%). With the exception of *Heat Density* where the proportion of references to adopt or discount were similar (10.9% and 12.5% respectively), these results indicate there were distinct themes presented by designers when deciding to either adopt or discount a HN. For instance, a designer was more likely to reference *future proofing* as a *motive to adopt* (37%) rather than as a *motive to discount* (7.7%). There were also themes that received little reference (i.e. <10%) in the assessment of a HN and others that were not reference at all.

For CHP the most prominent themes as a *motive to adopt* were: *CO_2 emissions* (35.6%), *Efficiency* (20.3%), followed by *Heat Density* (11.9%), *Economic* (11.9%) and *Planning Policy* (11.3%). Whereas, the most prominent theme for as a *motive to discount* were: *Heat Density* (40.6%), *Economic* (21.9%), and *Planning Policy* (12.5%). With the exception of *Planning Policy* where the proportion of references to adopt or discount were similar (11.9% and 12.9% respectively), these results indicate there were also distinct themes presented when deciding to either adopt or discount a CHP. For instance, a designer was more likely to reference *CO_2 Emissions* as a *motive to adopt* (35.6%) than as a *motive to discount* (1.6%). There were also themes that received little reference (i.e. <10%) and others that were not reference at all in relation to CHP.

6.2.3.2 Comparing Prior Theme and Emergent Themes

Comparing these emergent themes against the prior themes identified (see 6.2.2), it was found that the prior themes of HD (20.7%), Economic Assessment (16.3%) and DHL (5.8%) were represented within the themes identified. Whereas, AE and LHD were not represented. It is noted that the theme *Heat Density* included both terms that related to the energy value (kWh/m^2) and descriptive terms relating to heat demand within a development (*'heat demand', 'summer based load', 'hot water demand'*) and site size (*'dwelling density'*).

6.2.3.3 Analysing the Context of Emergent Themes

In this section, the excerpts of the documents are cross-referenced with the document reference number (see table 6.6) and a suffix of type of energy system selected ($^{\text{HN-CHP}}$, $^{\text{HN}}$, $^{\text{Other}}$).

Firstly, examining *Density*, which was formed of categories relating to both thermal (e.g. heat density, summer base load, hot water demand) and size (e.g. number of units, site density). When analysing this theme within the context to which the designers have applied it, what became apparent is that the designers' motives were generally a simple statement of a term (e.g. 'size, 'high density', 'low density', 'heat density'), without the quantitative value that these terms represent (m^2, kWh/m^2, etc.). Without these quantitative values these terms were found to lack context and the result is a notional concept of density. For example the following density motives were stated by designers: *"due to the size of the development, a communal heating system has been proposed" (19$^{HN\text{-}CHP}$); "the development has a reasonably high density which can make a site-wide heating network justifiable" (49^{HN}); "the relatively small number of units and low density the adopted approach is for heating…to be applied on an individual dwelling bases"* (27$^{\text{Other}}$). There is an example of where context is provided, one designer quoted the LPA guidance: *"Croydon Local Plan requires high density residential developments of* ***<u>20 or more units</u>*** *to incorporate a site wide communal heating system" (33$^{HN\text{-}CHP}$).* The quantitative value for 'high density' defined by the LPA provides a rational context to the designer's motive. For CHP several designers quoted the GLA *Energy Planning Guidance* (2016) suggested minimum density figures to discount CHP as a viable option (9$^{\text{Oth}}$, 11$^{\text{HN}}$ & 31$^{\text{HN}}$).

In relation to CHP, the context of density related to a 'consistent', 'continual' or 'base load' for heat within a development (*3$^{HN\text{-}CHP}$, 5^{HN}, 15$^{HN\text{-}CHP}$, 21^{Oth}, 23^{Oth}, 31^{HN}, 37^{HN}, 41^{HN}, 44^{Oth},* *45[Oth], 7[HN-CHP], 9[Oth], 14[HN], 25[HN-CHP], 46[Oth] & 48[HN-CHP]*). Again statements were generally notional and lacked any quantitative values or supportive information;

- "*[CHP] is both technically and economically viable since there is a year round demand for domestic hot water" (25[HN-CHP]);*
- *"the long operating hours will be ensured by the water heat demand" (7[HN-CHP]);*
- *"the hot water load into a consistent base load which can potentially be delivered by CHP technology" (48[HN-CHP]).*
- *"the base heating load has been determined to be insufficient to run CHP plant" (37[HN]);*
- *"[CHP] will not perform well where there is an inconsistent demand for heat" (3[HN-CHP]);*
- *"the building is 100% residential the load profile is not conductive to this technology, with only the demand for hot water being relatively consistent over the year to act as a base load for CHP" (31[HN]);*
- *"The demand for hot water from residential units will not be constant, as it will only be required at peak times in morning and evenings" (41[HN]).*

In the sample documents conflicting motives were identified when designers used the theme of density as a motive to adopt or discount CHP. Table 6.10 demonstrates that within the sample documents analysed the same theme was used as a motive to adopt or discount CHP in sites with similar unit numbers or whether a scheme was solely residential or mixed-use. Without these quantitative values or supportive information to this theme, developments lack individual context and the result is a notional motive for the adoption of a technology.

Table 6.10: Theme Density: Motives to Adopt or Discount CHP relating to the number of Domestic Units

Theme: Density			
Motives to Adopt CHP	***No. Units***	***No. Units***	***Motives to Discount CHP***
"Within this development, the long operating hours will be ensured by the water heat demand, which will be constant throughout the year." (7[HN-CHP])	29	21	*"Communal CHP is not viable for such a small development." (35[Oth])*
"The proposed development energy and heat demand profile is very likely to match this requirement, taking into account high density of the building" (33[HN-CHP])	42	25	"CHP was discounted for this development for as there is a low base hot water heating load expected through the year" (5[HN])
"Combined Heat and Power is both technically and economically viable since there is a year-round demand for domestic hot water within the proposed development." (25[HN-CHP])	55	25	*"CHP system would not be viable for such small development due to low peak demand" (43[Oth])*
"The estimated residential hot water demand is expected to present a consistent load throughout the year" (48[HN-CHP])	72	27	"*Full sized CHP would be inappropriate for the relatively small load" (17[Oth])*
-	-	29	*"It is also expected the heating and electrical daily load of the building will be insufficient for a CHP system, and as a result, a CHP system will not be considered for the development." (44[Oth])*
-	-	45	*"the smallest commercially available CHP unit is too large for the scheme due to the limited number of residential dwellings" (32[HN])*
-	-	50	*"A CHP system would not be viable for this scale of a project due to low peak demand. Also, as the proposed scheme includes only residential units the peak demand would be in morning and evening only" (50[HN])*
-	-	69	*"The heat demand profile of this residential scheme is not suitable to CHP. The implemented fabric improvements from the 'Be Lean' scenario have also reduced the energy demand from space heating to hot water." (40[HN])*
-	-	124	*"Given the size of the development it is not feasible to introduce a CHP plant, to provide heat and electrical energy to the development." (11[HN])*

One of the prominent findings of the analysis is that in regards to smaller sized developments (<150 residential units) there is no clear professional view to what size a HN and CHP are deemed viable; whereas the findings suggest that larger developments (>150) are almost certain to adopt a HN and likely to adopt a CHP. There are clear references within planning policy guidance, academic research, industry design guidance, and many examples presented by the designers of the ES documents that HNs, and more specifically CHPs, are only suited to large, high density, high energy (heat and power) demanding developments. However, the findings from the documents sampled would suggest that a development of any size has been deemed suitable for either a HN or HN-CHP. Figure 6.6 presents the analysis of the sample documents that demonstrate that site density appear to have little inference on the possible selection of HN and HN-CHP.

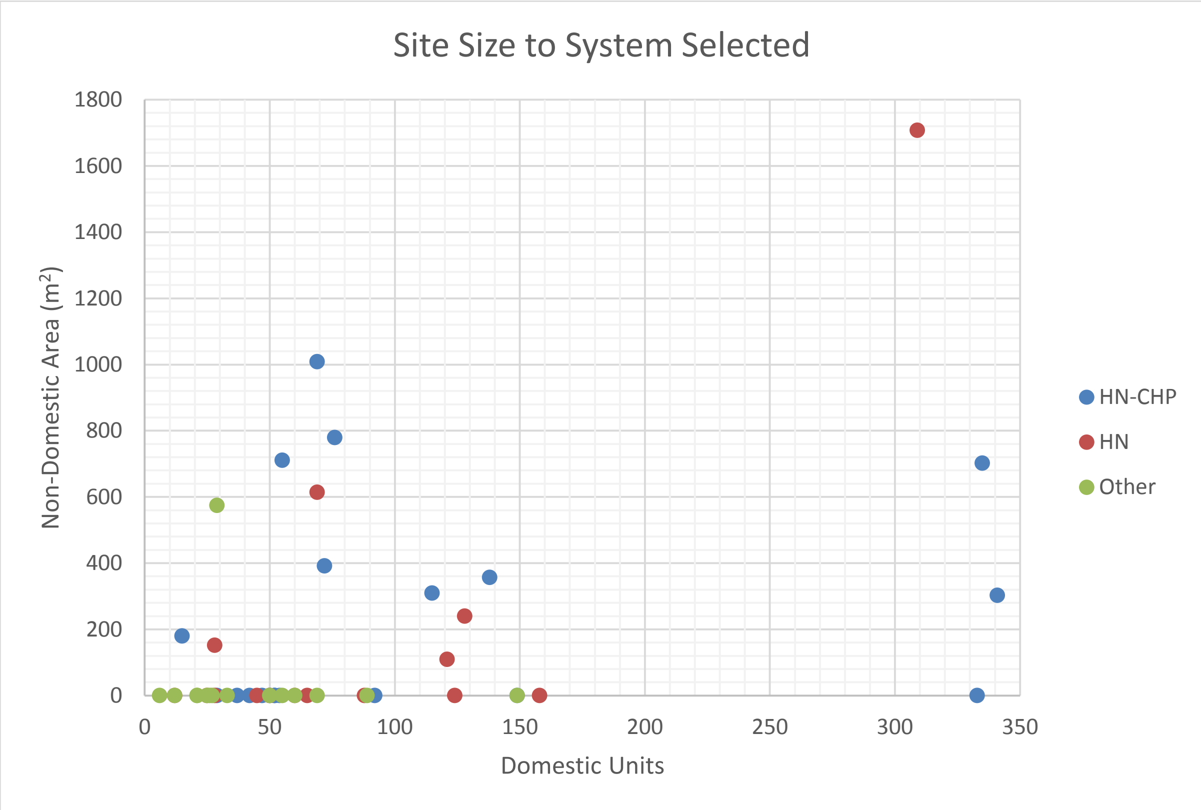


Figure 6.6: Site Size Related to Energy System Selected

Figure 6.6 demonstrate there is no obvious relationship between a development's size and type of energy system selected. Developments with greater than 100 dwellings are likely to adopt a HN or HN-CHP rather than any other technology.

Economic viability is the second most prominent theme which consisted of categories relating to capital costs, operational costs, fuel costs, economic assessment and discussions including available government financial grants. It was found that economic motives were used predominately against the adoption of a HN (25.6% verse 6.5%). Designers' motives regarding the *Economics* of a HN were generally related to the capital and operational cost. These were judged by two factors; 'economies of scale' and the evaluation of '[energy] savings versus additional costs'. Several of the ESs stated that the capital cost of a HN is more expensive than an individual boiler system (12^{Oth}, 36^{HN}, 43^{Oth} & 47^{HN}). There was one estimate of +£2,000 per dwelling (15[HN-CHP]). Larger developments were said to benefit from 'economies of scale', whereas smaller developments would see costs increase, as costs are shared between fewer consumers (46[Oth]). Other measures such as 'fabric improvements' were said to have a greater saving and thus be "*more cost effective"* (43[Oth]). One designer argued that *Economic* influences are significant for the decision to adopt a HN stating that *"capital costs must be insignificant to support viability"* (45[Oth]).

Costs for consumers were also generally argued to be higher for a HN as 'fixed costs' associated with management, operation and depreciation of a HN must be shared between consumers (46[Oth], 23[Oth]). This was linked to economies of scale as the "*fewer the number of units, the greater the cost for the individual occupant"* (46[Oth]). Only one designer argued that operational costs would be reduced by adopting a HN (*22[HN-CHP]*). In relation to consumer fuel costs, one designer quoted "*twice the cost of a kWh"* for heat in a HN compared to individual gas boilers (*28[Oth]*). Another designer claimed that anecdotal evidence suggested that heating bills were not lowered and in some cases were higher (*28[Oth]*). Others identified the cost implications of managing a HN. For example, engaging a third party billing company as the owner was not able to provide this facility "*in house"* (*28[Oth]*). It was further explained that the debt risk remains with the HN owner for unpaid heat bills and this was a *"huge risk"* (*28[Oth]*). Others identified potential savings from a HN (*36[HN], 22[HN-CHP]*) with one quoting *"circa £150/annum/boiler*" from removing gas within individual dwellings (*36[HN]*).

The economic arguments relating to CHP were commonly discussed (35.8%), suggesting economic reasoning as a main influential factor in decision making regarding CHP. This is summed up by one designer who stated "*merits or otherwise of incorporating CHP is usually determined by strict economic viability*" (6[HN-CHP]). This may support why economic motives were used more often to discount CHP (21%) than to adopt (12%) CHP. The economic discussions were found to represent a range of different perspectives, some on the basis of capital or operational costs (*3[HN-CHP], 27[Oth], 14[HN] & 15[HN-CHP]*). For instance, *"Up-front and ongoing costs are higher than commercial gas boilers"* (*3[HN-CHP]*). Others linked economic viability to heat demand (*18[HN], 23[Oth], 6[HN-CHP] & 40[HN]*). For example, *"The economic viability of a CHP system is largely reliant on a consistent demand for heat throughout the day"* (*23[Oth]*). Whereas others linked economic viability to the utilisation or export of generated electricity (*6[HN-CHP], 22[HN-CHP], 16[Oth], 26[HN-CHP] & 46[Oth]*). For example, *"From an economic point of view it is advantageous to use the generated electricity onsite rather than selling to the grid" (6[HN-CHP])* and “*It is uneconomically viable to export such large quantities of electricity this option is unviable” (16*[Oth]*).* Some linked economic viability to the site density (*32*[HN]*, 35*[Oth] *& 43*[Oth]). One designer considered viability on economic pay-back, arguing that *“a sample economic payback less than 20 years, leading to the conclusion that CHP is a viable proposition for this site”* (*6*[HN-CHP]).

The *Economic* theme identified that there are extensive, complex and sometimes interconnected economic variables that designers related to HN and CHP. Given the significance that some designers clearly attribute to economic viability, “*merits or otherwise of incorporating CHP is usually determined by strict economic viability*” (*6*[HN-CHP]), what is surprising is that the majority of documents (83.7%) made no reference to the *Economic* theme. The results from the pre-set themes showed that only 10% referenced an economic assessment and only 2% included verifiable data. The analysis of the literature found that economic as well as technological viability was essential for the assessment of CHP (chapter 3). The analysis here identified in the case of CHP, a conflict among the effective use of generated electricity. As established earlier, there are difficulties with creating revenue from small-scale CHP. The Carbon Trust (2004) identified that where designers have ignored the electricity demand in the sizing of a CHP, they have inadvertently ended up exporting power and not getting any revenue from the export. Kelly et al, (2010, p.18) found that for small to medium scale CHP plant, exporting electricty is prohibitively expensive. Therefore, in many residential CHP installations electricity generated is restricted to supplying electricity to the central plant room and other landlord services within the development. Table 6.11 outlines the various means by which the designers proposed to use the electricity generated by the CHP. The results show that the designers expressed conflicting options regarding how the electricity generated can be utilised.

Table 6.11: The Proposed Use of CHP Generated Electricity

Proposed Use of CHP generated Electricity	**Onsite / Export**
"From an economic point of view it is advantageous to use the generated electricity on site rather than selling to the grid"…"55% of the site's electricity demand…can be met by the CHP system"… "it is assumed that 90% of all the generated electricity can be used on site to supply the apartments." (6[HN-CHP])	Onsite
"the system would be required to export over 70% of the electricity it generates as the development's thermal and electrical load profiles are unbalanced. As it is uneconomically viable to export such large quantities of electricity this option is unviable" (16[Oth])	Export
"The two CHP engines will also provide approximately 31 MWh of electricity, approximately a quarter the proposed developments load, which shall be used throughout the development via a distribution board" (13[HN-CHP])	Onsite
"The small size of the scheme and a lack of commercial space means that there is no electrical load and a CHP would not be appropriate." (20[HN])	Onsite
"Therefore there is a single electricity supply to the whole of the TA building which allows the economical use of combined heat and power, where the power is used by the TA building." (22[HN-CHP])	Onsite
"it would require the export of electricity to the grid. It is considered that the administrative burden of managing CHP electricity sales at this small scale … is too great for operators of residential developments to bear. For these reasons a site-wide CHP system is not considered feasible." (23[Oth])	Export
"It is proposed to install an electricity demand led CHP which has been sized to suit the baseline electricity demand of the development based on the estimated electricity consumption demand profiles." "Produced electricity can be exported to grid if the on-site demand is lower than production." (24[HN-CHP])	Onsite & Export
"CHP works with central boiler plant and although it adds substantial costs to the installation this is projected to pay back within eight years assuming a grid export rate of 8p/kWh. The small scale of the CHP and the large landlord electrical requirements of the communal space means that it is likely the payback will be shorter, as the CHP will off-set grid supplied electricity at 12p/kWh" (26[Hn-CHP])	Onsite & Export
"The electricity generated would be used for landlord's services and/or exported to the national grid." (27[Oth])	Onsite and/or Export
"Electricity export price 5p/kWh" (29[Hn-CHP])	Export
"Produced electricity can be exported to grid if the on-site demand is lower than production." (34[Oth])	Onsite & Export
"The 33 kWe size of gas CHP unit is inappropriate for the site due to the profiles of domestic energy consumption and reduced commercial area providing an electrical base load" (36[HN])	Onsite
"The excess electricity generated by the CHP unit will be exported to the grid, which almost offsets the grid electricity imported during the night period." (39)	Export
"Because of the small electricity supplies and demand of this scheme, a CHP installed to meet the base heat load would typically require the export of electricity to the grid. The administrative burden of managing CHP electricity	Export

sales at a small scale…. is prohibitive for smaller operators of residential developments." (40[HN])	
"Electricity generated displaces power that would otherwise be sourced from the Grid." (45[Oth])	Onsite
"Onsite use of CHP generated electricity; power Purchase Agreement with electricity Supply Company or Private Wire arrangement to local large nondomestic demand enhances economic case." (46[Oth])	Onsite & Export
"When there is a sufficient electricity demand in the landlord areas, the electrical output of the CHP system will be fully utilised on site with no export to the grid. If the electricity demand is lower than the electricity supplied by the CHP unit, the surplus will be exported to the grid." (48[HN-CHP])	Onsite & Export

A variety of economic motives has been identified, although the results demonstrated that only a few documents included more than one of these motives. Currently there is a lack of economic analysis being undertaken. It could therefore be argued that an essential step in the viability assessment of HN and CHP is being overlooked. Furthermore, the different proposed uses of CHP generated electricity suggests there is a lack of professional consensus of what is technically and economically the optimum use. The results also show that there is suggestion of wider long term economic effects regarding the 'complex management', 'heat costs' and 'bad-debt risk' associated to these technologies that currently do not feature in the mainstream motives presented by designers or policy guidance.

Examining the themes of *CO_2* and *Efficiency*, the results show that these only related to the initial process of energy generation (i.e. heat from boilers or heat and power from CHP), rather than the overall process of heat generation and distribution (HN) or heat and power generation and distribution (HN-CHP). HNs and HN-CHP involves the process of generating thermal energy and distributing that energy to consumers. The analysis showed there were only a few references made to *CO_2 emissions* as a *motive to adopt* a HN. Furthermore, there were no statements presented that suggested a HN would increase CO_2 in a development (over a traditional individual heating system). Of the two designers that suggested CO_2 can be minimised with the use of HN, this was stated as only in conjunction with a CHP (*8[HN-CHP], 10[HN-CHP]*). *Efficiency* was found to be a more common as a positive argument for the adoption of a HN. The designers claimed that higher energy efficiencies can be achieved from larger scale boilers over smaller individual boilers (*15[HN-CHP], 23[Oth] & 27[Oth]*). The majority of statements referred to the efficiency of the heat generating plant rather than the distribution of heat. However, one designer suggested that the HN "balanced" the heat loads, allowing the heat generating plant to operate continuously resulting in higher efficiency (*45*[Oth]). This example again relates to the efficiency of heat generation rather than distribution. In only one document was the individual boiler stated to be the "*most efficient*" solution (*12*[Oth]). The lack of discussion or assessment of the efficiency relating to the distribution of heat and resulting the CO_2 is surprising given the GLA policy intention through the 'energy systems hierarchy' to select energy systems based on efficiency and CO_2 reduction potential.

CO_2 emissions reduction was the most common motive stated in support of adopting a CHP, being over a third of all themes (36%). Several designers quoted potential reductions of between 20-30% compared to conventional systems (*6*[HN-CHP]*, 22*[HN-CHP]*, & 26*[HN-CHP]) and one suggested savings up to 50% (*41*[HN]). A number of the designers identified that the electricity generated by the CHP was the key factor in achieving CO_2 savings (*3*[HN-CHP]*, 14*[HN]*, 27*[Oth]*, 39*[HN] *& 45*[Oth]); as explained by one designer who acknowledged that the heat produced by a CHP would result in an "*extra 235 tonnes of CO_2 per year*" but this would be "*more than offset by a saving of 328 tonnes* of CO_2" from displacing grid electricity (*39*[HN]). It was commonly identified (20%) that the CO_2 savings resulted from the increased efficiency achieved in a CHP over conventional energy systems (*1*[HN-CHP]*, 3*[HN-CHP]*, 4*[HN-CHP]*, 14*[HN]*, 41*[HN]*, 48*[HN-CHP] *& 49*[HN-CHP]). Whereas some statements simply referred to a notional statement of 'high efficiency' (*1*[HN-CHP]*, 3*[HN-CHP]*, 4*[HN-CHP] *& 47*[HN]), others elaborated suggesting that CHP achieves greater efficiency over conventional heat and power generation (*17*[Oth]*, 21*[Oth]*, 36*[HN]*, 41*[HN]*, 42*[HN]*, 48*[HN-CHP] *& 50*[HN]); *"CHP effectively uses waste heat from the electricity generation process to provide useful heat for space and water heating; the advantage of this system is that it leads to higher system efficiencies when compared to a typical supply arrangement of grid-imported electricity and conventional boilers" (42*[HN]*).*

These results suggest that the motives specifically regarding the *Efficiency* and *CO_2 emissions* of HN and CHP are focused primarily on the generation of heat, and in the case of CHP, power also. Chapter 3 identified that a HN is a process of both energy generation and distributing energy to consumers. These findings are important as previous research has found that the distribution of heat often consumes more energy than predicted through DHL and AE. Although DHL has been identified as a separate theme (next paragraph), DHL and AE can be argued to be an essential part of any efficiency and CO_2 calculation. Therefore, it can be argued that currently insufficient feasibility assessment of a HN and CHP is being conducted. These distribution losses are particularly important when comparing efficiency and CO_2 to individual heating systems, which do not require a primary distribution system. This was acknowledged by one designer "*CO2 savings gained within the dwelling through association with CHP may be considerably reduced by the additional losses associated with the network"* (*46*[Oth]).

The theme of *Distribution Heat Loss* was the most frequent motive used to discount a HN. Despite this, DHL only represented a small proportion (5.8%) of the overall themes identified in the sample. It was a consideration for directly comparing the selection of a HN over individual heating systems, the principal suggestion being that "*heat is wasted in distribution networks*" and *"heat losses often experienced with a district network"* reducing the efficiency of the HN system (*1*[HN-CHP]*, 17*[Oth]). One designer expressed their existing experience of a HN, stating that heat loss in distribution pipes is a significant problem that "*we*" have (*28*[Oth]). Another argued that heat loss from distribution pipework was the reason why *"often energy savings are not realised in full"* (*22*[HN-CHP]). There were only a few designers who commented on the proportion of losses. One quantified DHL in the region of 5% to 15% of heat demand (*23*[Oth]), supported by another that stated 10% (*25*[HN-CHP]). Another suggests potentially higher losses "*standing heat losses, as are even the best insulated heating distribution networks. When communal systems satisfy a small and intermittent demand, these standing losses will represent a large part (often over 30%) of total demand*" (*46*[Oth]). DHL was also related to HD, with one designer commenting that HNs are only generally feasible where there is a "*high density for heat*" (*45*[Oth]). A similar argument was made that "*individual houses not generally suitable"* for HN (*9*[Oth]). It was also said to, in part, effect the viability of CHP; *"Integration of CHP to this development would not be technically or economically viable due to a low and infrequent heat demand and high relative distribution losses."* (*45*[Oth]). There were a number of references to secondary issues of 'overheating' (*49*[HN-CHP]*, 28*[Oth]*, 22*[HN-CHP]*, 26*[HN-CHP] *& 23*[Oth]) and increased service charges for occupants (*26*[HN-CHP]).

What is relevant for this research is the lack of critical discussion regarding the theme of DHL in the feasibility assessment. It is clear from the ESs reviewed that losses can be a significant issue, with one designer suggesting a potential relationship to the EPG - *"Although a communal heating system is preferred heating option for large residential developments, often the energy savings are not realised in full because of the heat loss from distribution pipework"* (*22*[Oth]). Furthermore, the wide variation in potential losses identified (5% to 30%) suggests there is a general lack of understanding and/or technical assessment regarding the level of DHL that can occur. There was only one reference linking HD to DHL, which may suggest why the prior theme of LHD was not referenced in any of the sample documents.

Adopting a HN to 'future proof' a development was the most frequent theme used. Future proofing was suggested to either allow future connection to a local offsite DHN or allow flexibility of fuel supply. For future DHN connections some designers identified existing or planned networks where they argued a connection could be made (*20*[HN], *31*[HN]). Others found that there were no existing or planned networks, but still planned to adopt a HN to allow a possible future connection (*13*[HN-CHP], *4*[HN-CHP], *41*[HN] & *48*[HN-CHP]). Two designers argued that a HN should not be adopted as there was no existing or planned network (*23*[Oth] & *34*[Oth]). One quoted the GLA guidance that there was no *"reasonable expectation"* of a network in the future (*23*[oth]). The other identified that future proofing allowed flexibility of fuel supply (*36*[HN], *19*[HN-CHP], *15*[HN-CHP] & *6*[HN-CHP]). However, no designers gave any examples of possible alternatives fuels or technology.

Future proofing is relevant to this research as it was the most frequent theme used as a *motive to adopt* a HN. However, this research found that where a HN or HN-CHP was proposed only 2% were in areas where there was an existing DHN. 14% were in areas were a DHN was planned. However, 38% were in areas where there was no existing or future planned heat network. 16% did not evaluate local DHN existed or was planned. These findings are illustrated in figure 6.7. These results suggest that in many cases although the designers recognise that there is no possibility of a future connection, a primary motive to adopt a HN is that it future proofs the development. It could therefore be considered that future proofing is used as an arbitrary justification for the adoption of a HN and is accepted as equivalent to technological or economic assessment.

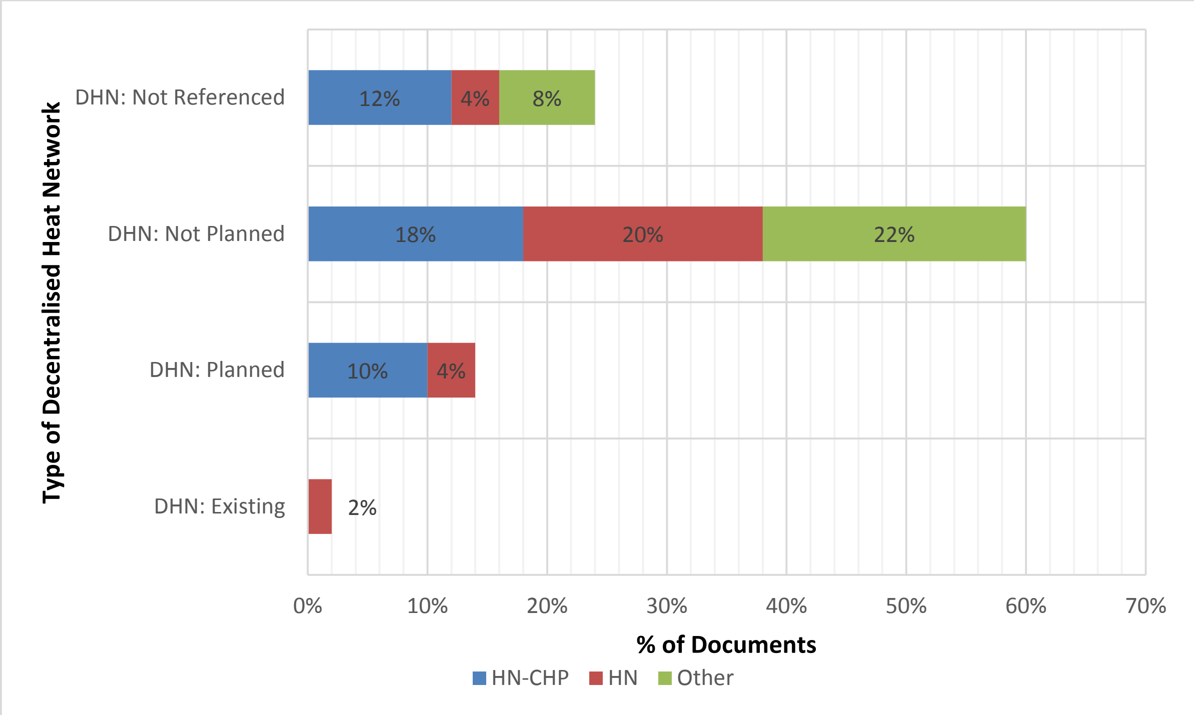


Figure 6.7: The Availability of Local Decentralised Heat Networks Related to the Selection of an Onsite Energy System

The theme *Planning Policy* considered all motives used by the designers that related to planning policy or SPG documents. This was another common motive for adopting a HN (15.2%). There were a number of statements that suggested that a HN is favoured by the Mayor's energy strategy ($13^{\text{HN-CHP}}$, 14^{HN} & 39^{HN}), as well as wider national, regional and local policies ($7^{\text{HN-CHP}}$ & $29^{\text{HN-CHP}}$). One directly quoted a LPA's minimum density target for incorporating a HN as the justification for adopting a HN ($33^{\text{HN-CHP}}$). Another quoted the CO_2 factor for heat (0.15 $kgCO_2$/kWh) stated in the local decentralised energy master plan (31^{HN}).

For CHP, the theme of *Planning Policy* was relatively even, representing 11.9% (adopt) and 12.5% (discount). Several designers quoted the GLA *Energy Planning Guidance* (2016) which suggested minimum density figures to discount CHP as a viable option (9^{Oth}, 11^{HN} & 31^{HN}). Conversely, others quoted the planning CO_2 reduction targets or the energy hierarchy as a *motive to adopt* a CHP ($1^{\text{HN-CHP}}$, $6^{\text{HN-CHP}}$, $7^{\text{HN-CHP}}$, $26^{\text{HN-CHP}}$, $29^{\text{HN-CHP}}$).

These significant findings are relevant to this research as it has been demonstrated that policy can be an influence on the designer's assessment of HN and CHP. Although policy has not been found as the most prominent theme, over 10% of the sample documents did refer to policy as a motive in the assessment of HN and CHP. The particular references to site density figures stated by LPA's and the GLA's guidance suggests that designers are able to use these figures as a simple arbitrary method of assessment for HN and CHP.

6.3 Reflection on Document Analysis Findings

The document analysis was undertaken to understand how policy is being applied in practice through an ES document; how the designers have assessed HN and CHP; and the motives that have guided the designers' decisions to either adopt or discount these technologies. The findings of this document analysis are considered in relation to the research questions posed in chapter 5 and how these findings guide the next stages of the research inquiry.

Secondary Question 1: *How do local energy policies influence the selection of low and zero carbon technologies?*

The earlier analysis of existing research (chapter 2) suggested that policy has a direct influence on the type of technology selected. It was observed that the changes to the energy hierarchy that prioritised CHP lead to an increases in CO_2 savings reported from CHP and in contrast to declining levels of savings from RE technologies. All of the sample documents analysed used the energy hierarchy as the chronological method by which technologies were assessed. Therefore, all of the sample documents provided an assessment of HN and CHP prior to the assessment of other technologies. The analysis has shown that some of the designers reported 'technology conflicts' as a motive not to assess certain technologies once a HN or HN-CHP had been deemed viable. The technology of solar thermal was identified as the main conflict with CHP. For example, *"CHP is not compatible with some renewable technologies, such as solar thermal as they both supply the base heat load, which is domestic hot water (DHW) demand in residential developments."* (*17^{Oth}*) and *"however solar thermal technology would compete with any future connection with a district heating network and therefore reduce benefits, and therefore this technology has been discounted"* (*31^{HN}*). The analysis has identified that the prioritisation of HN and CHP in policy can result in other technologies not being assessed or being assessed on the basis of compatibility with HN or HN-CHP, rather than on their individual merit to reduce CO_2. Consequently, this can restrict the level of overall technical feasibility assessment being undertaken.

The analysis of designer's motives to either adopt or discount HN and CHP found that over 10% of the sample used planning policy as a motive in their assessment. This suggests compliance with planning policy is being used a legitimate justification for the adoption of a technology and therefore the equivalent to technological or economic assessment.

The implementation of HN-CHP in practice indicates a level of bias based on policy rather than technical or economic assessment. The next step in the evaluation of policy influence would be to identify, through engagement with the designers, the degree to which designers believe policy has influenced their decisions regarding the selection of HN and CHP. The industry surveys (chapter 8) present the findings to this inquiry.

Secondary Question 2: *What are the motives for the adoption of a Heat Network and CHP in a new residential development?*

The document content analysis found that several prominent themes emerged as motives to either adopt or discount HN and CHP. *Density* was the most prominent theme, followed by *Economic* considerations. The subject of the most prominent themes were perhaps not surprising given the purpose of the ES, as defined by the GLA (2016), is to demonstrate that climate change mitigation measures comply with TLP policy, including the energy hierarchy. Therefore, it would be reasonable to expect that an assessment would include *Heat Density*, *Economic*, *CO_2 Emissions*, *Efficiency*, *Planning Policy,* and *Future Proofing* as relevant themes. However, what was unexpected is the low frequency that these themes appeared in the sample of documents.

The analysis found that the themes were more often presented as notional concepts, devoid of technical justification or quantitative value to support the designer's assessment and decisions. The analysis found that none of the sample documents provided verifiable data for HD and only 2% provided verifiable data of an economic assessment. Without technical justification or quantitative values it was found that the sample developments lacked individual context and the result is a notional motive for the adoption of a technology. Terms such as *"due to the size of the development"* were common notional motives presented. However, examples in the sample found conflicting presumptions by the designers referring to sufficient density to support CHP and conflicting presumptions over how electricity generated via a CHP can be utilised. It is therefore unlikely that the motives presented by the designers could be corroborated in every case by any rigorous technical or economic interrogation. This is important for this research as it is the GLA's policy that no further feasibility work should be undertaken after planning, and furthermore, that the implementation of the proposed ES should be secured through planning conditions. The opportunity for rigorous technical or economic assessment is therefore at the planning stage, which is not currently being undertaken.

The next stage of the research inquiry will examine how the identified designer motives relate to operation in practice. In relation to density and efficiency the case study presented in chapter 7 examines the performance in practice to determine if an EPG exists and what, if any, are the implications to the designers motives that have been presented in the sample documents. The survey presented in chapter 8 engage directly with the designers to seek greater detail and understand of the influences behind the motives they presented.

Secondary Question 3: *Do local energy policies promote appropriate feasibility assessment of Heat Networks and CHP?*

The earlier review of the planning policy and guidance presented in this thesis found that the GLA suggests that there is sufficient information available through published planning guidance for designers to complete an economic and technical assessment of the proposed measures.

TLP states that reductions in CO_2 are required to be reported against a building regulations baseline design and therefore require the adoption of regulatory models. It has been established through the analysis of the sample documents that the regulatory model (SAP) was in fact the main energy model tool used. There was only one example of a secondary tool being used to justify the adoption of a CHP. This result is important in the context of existing academic and industry research that has suggested that regulatory tools are not accurate at predicting energy usage and are one of the primary causes of the EPG (see De Wilde et al, 2014; Carbon Trust, 2011; Menezes et al, 2012; Van Dronkelaar et al, 2016).

The findings presented provide an indication of the direct influence that energy policy has, not only on the technology assessed, but also the energy calculation tool employed by designers in the feasibility assessment of HN and CHP. The finding that the assessment is solely based on the regulatory model, without other technology specific assessments methods, suggests a practice of policy compliance rather than detailed technical assessment.

Chapter 3 provided an examination of the academic research and industry design guidance relating to the feasibility assessment for HN and CHP. This examination identified key factors that designers should take into consideration during a feasibility assessment. This included: HD, LHD, economic viability, and energy demand profiles. The results of the document analysis showed that these key factors are not being routinely considered by designers during their feasibility assessment of HN and CHP. The findings also showed that even where designers have considered these factors, they were presented as notional concepts unsupported by technical justification or substantiated quantitative data. Therefore, in the absence of a defined method by the SPG or designers adopting recognised academic and industry assessment methods, it is currently unknown by what method, if any, designers are undertaking a technical and economic assessment. Furthermore, without verifiable data it is unknown how the claims presented by the designers for the adoption or exclusion of HN and CHP are technically and economically justifiable. Consequently, there is no robust assessment that CO_2 reductions are achievable in practice.

There is already evidence that performance is not being delivered in practice. The results of this document analysis found that DHL as well as AE, two factors that are fundamental to the energy consumption and thus CO_2, are not being routinely examined as part of the assessments. The exclusion of detailed calculations and limited recognition of these factors may undermine the performance of HN in practice, if those tasked with implementing the ES are not aware of the influence of these factors have on performance in practice. Consequently, an inefficient HN may not be able to reduce CO_2 compared to individual energy systems despite a CHP (or RE) providing the source of heat.

The next stage in this research enquiry will be to investigate if an EPG exists in HN-CHP systems, and if so, what are the causes of the EPG. The outcome of this enquiry is presented through the case study in chapter 7. The research enquiry will also engage with designers (chapter 8) to identify the level of expertise and experience relating to a HN and CHP of the designers undertaking the feasibility assessments; understand what the technical assessment of a HN and CHP should include; and their opinions to whether planning energy policy is delivering the energy and CO_2 reductions in practice and their opinions on if an EPG exists and if so what are the causes.

The findings of the document content analysis have shown that the assessment of HN and CHP is predominantly based on the use of regulatory models and justified mainly through notional concepts. The documents sampled were shown to include a limited level of detailed technical assessment specific to HN and CHP. Identification of key performance factors described in academia and industry were mainly absent. These findings suggest that planning energy policy has a direct influence on types of technologies being assessed and also the detail of feasibility assessment being undertaken. The designer's selection of HN and CHP on the basis of planning policy has been shown to be perceived as an equivalent justification to detailed technological and economic assessment. However, without appropriate assessment of HN and CHP it is unknown if the reductions in energy and CO_2 presented by the designers in the ES would stand up to any rigorous technical or economic interrogation and furthermore, if they are achieved in practice.

6.4 Chapter Reflectance

This chapter has presented the first stage in the primary research enquiry. A systematic method for undertaking a document content analysis was presented and was undertaken. The purpose and objectives of the analysis were defined. Criteria of selection were established to ensure the documents that were selected were suitable for the analysis and would provide credible findings. Prior and Emergent themes were identified and a coding method explained and implemented. The results of the coding analysis were presented in statistical and graphical form. The results were reflected on and findings were compared to the research questions presented in chapter 5. This chapter has provided empirical evidence that will support the answering of the research questions and have helped to direct the next stages of the research enquiry.

CHAPTER 7: POST-OCCUPANCY ENERGY ANALYSIS OF A HN-CHP SYSTEM

This chapter provides a systematic analysis of the energy consumption and resulting CO_2 for the provision of domestic space heating and hot water via a HN-CHP system in a residential building. Methods are presented and applied for the analysis of different elements of the system to determine performance in detail. The performance is evaluated against predicted performance defined in the case study energy strategy and regulatory performance calculations (SAP). The dual purpose of the case study is to examine if an EPG is observed, and where so, to identify the specific elements of the HN-CHP system where the EPG exists. Secondly, to examine if a pre-planning feasibility assessment based on the defined energy performance indicators (EPI) could have provided a more realistic assessment of performance in practice. The chapter concludes by reflecting on the evidence and its contribution to the research.

7.1 The Case Study Method

Case Study (CS) research is a scientific method of investigating a real-life phenomenon within its environmental context *"especially when the boundaries between phenomenon and context are not clearly evident."* (Yin, 2009, p.18; Ridder, 2017).

Yin, (2012) describes three situations where CS research method can be applied. Firstly, descriptive questions (what is/has happened?) and explanatory questions (how/why something happened?), whereas determining a specific outcome and frequency is suited to more quantitative methods of research. Secondly, when focusing on a phenomenon in its real world context, a CS is favourable as data are collected in the natural setting as opposed to reliance on derived data (instrumental experiments). Thirdly, for conducting evaluations a method that is common with governmental research.

Flyvbjerg (2006) describes how CS research may lack appropriate theory, rigour, validity, and reliability to be considered a primary research method. However, Flyvbjerg considers these to be misunderstandings of case study research. Table 7.1 below outlines the five misunderstandings of case study research and provides Flyvbjerg's contrary perspective.

Table 7.1: Flyvbjerg's (2006) Five Misunderstandings of Case Study Research

Misunderstanding	Contrary
1: General theoretical (context-independent) knowledge is more valuable than concrete practical (context-dependent) knowledge.	1: Research into human learning demonstrates that context-dependent knowledge is necessary to achieve expert learning in a subject. Therefore, context-dependent knowledge and experience are at the centre of expert activity; Case Study provides this type of knowledge. This is specifically applicable to social science where human behavior cannot be meaningfully understood as simply rule governed.
2: One cannot generalise on the basis of an individual case, therefore case study cannot contribute to scientific development.	2: The contrary argument lies within three propositions; firstly, it is possible to generalise from a single case where the components of the case have been strategically chosen to form a critical case. Secondly, that the non-generalisation of research does constitute that it cannot enter the collective process of knowledge accumulation. Finally, that case study is ideal for generalisation when considering Pooper (1959) 'falsification'.
3: The case study is most useful for generating hypotheses, which is in the first stage of a total research process, whereas other methods are more suitable for hypotheses testing and theory building.	2: This argument also relates to the ability to generalise when hypothesis testing, which has been demonstrated in case study research to relate to strategic case selection.
4: The case study contains a bias toward verification, that is, a tendency to confirm the researcher's preconceived notions.	4: Flyvbjerg (2006) argues: "The case study contains no grater bias towards verification of the researcher's preconceived notions than other methods of inquiry. On the contrary, experience indicates that the case study contains a greater bias towards falsification of preconceived notions than verifications."
5: It is often difficult to summarise and develop general propositions and theories on the basis of a specific case study.	5: This proposition is generally accepted, although it is argued that this is not a criticism of the case study as research method. Instead it is the nature of the case process and properties of the case being studied that may make it undesirable to summarise or generalise. Furthermore case studies should be read as a narrative in their entirety.

Although, CS research is often associated with qualitative research, this is not essential as it can employ solely quantitative data (Creswell, 2009). However, commonly it employs a combination of both qualitative and quantitative (Bryman, 2008 p.53). Similarly, CS can employ multiple research paradigms in a single case or be expanded to engage multiple cases consecutively (inductive) or concurrently (deductive) (Dooley, 2002). The advantage of a multiple CS is the ability to complete cross-case analysis through a systematic comparison of findings (Ridder, 2017). Multiple CS provide a means to advance theories by comparing similarities and differences among the range of examined cases, whereas, a single CS is able to contribute to theory by examining and expanding constructs and relationships with distinct detail and its natural setting. Burns (2000; p.459) warns that this diverse application of CS can sometimes lead to a 'catch-all' approach for research that does not fit experimental, survey or historical methods (Ridder, 2017).

The advantages of a single CS is the depth of analysis and description that the research can apply to the case. A single CS has the potential to open a "black box" which unleashes a richer description and understanding of the "how" and "why" of the examined phenomenon (Ridder, 2017). By this approach, the chosen 'case' would not be a random sample, but would be chosen directly for its 'interest' (Stake, 2005) or chosen for theoretical reasons (Eisenhardt & Graebner, 2007).

Yin (2012) states the selection of a single or multiple-case is a primary distinction to be made in CS design. There is potential vulnerability in a single-case design:

- Misrepresentation of the case
- A lack of available evidence, and
- A single case cannot be regarded as a completed study on its own.

A '*critical case*' can be considered an appropriate adoption of single-case analysis, as it can be used to confirm, challenge or extend a theory proposition. A single-case is used to determine whether the propositions are correct or if alternative relevant explanations exist. In this manner, the case can represent a contribution to the wider knowledge and can help refocus future investigations in a research field (ibid).

The specific phenomenon of this research lies within the 'real world' context of the construction industry and the built environment. The research investigates the real world phenomena of the EPG in low energy residential buildings with HN-CHP. Furthermore, the research aims to understand how a gap is influenced by early design decisions by those participating in the real world. The examination of this phenomenon in its real world context through the methodology of case study research is therefore considered appropriate. The use of a critical-case rather than a multiple-case study approach is justified in the richness of data and in-depth analysis that can be undertaken. Amaratunga et al (2002), believe that CS research has an important function specifically in the built environment, where a detailed case can provide intimate understanding of process or behavior which are little understood. The aim of this CS research is not simply to add multiple examples to the growing body of academic literature related to the EPG. This research has already demonstrated through the examination of primary and secondary data, that an EPG can exist in HN and CHP systems. The research intention to use the CS as part of a wider strategy of inquiry to examine if an EPG exists in the critical case, and therefore can make a modest contribution to the research field of POE. Secondly, the case will describe how early stage feasibility assessment might have influenced the predicted performance and perceived scale of the EPG, thus contributing and expanding the field of knowledge of research.

The application of single-case research has precedent within the evaluation of energy performance of buildings. For example Jones et al (2016) conducted a case study of a site to determine the gap between simulated and measured energy performance. Nooraei et al (2013) used semi-structured interviews and spot temperature measurements to gain feedback on occupants' thermal comfort in a single case study building. Birchall (2011) used measured energy data, occupant surveys, focus groups, and observations to appraise the performance of a low energy office building. Kondidari (2017) explored the influence of architects on operational energy use. All of these represent a contribution to the wider knowledge.

7.2 Identification of the Case Study

O'Leary (2004) suggests that selecting the right case is one of the most crucial decisions. Whether selected for intrinsic value or because it is representative, the selected case must provide sufficient data to make appropriate analysis. Yin (1994, p.25) suggests that the selected case should either be similar to existing cases, or deviate in defined ways. These two approaches allow the researcher to use previous literature to help define the new case and its relevance to its field (Dooley, 2002). The case selected for this research must be representative of the clearly defined boundaries described earlier (section 6.1.2). Therefore, the case selected can be deemed to be representative of many developments built in

London under the TLP energy policy. Therefore, this case will provide similarities to existing studies. Where this case deviates from the existing is the in-depth analysis of specific EPI that will describe individual performance aspects of the HN-CHP system. Furthermore, through these indicators the CS will determine if the observed performance could have been expected at feasibility stage.

Dooley (2002) advises that it is important that the researcher acknowledges any personal involvement in the research data, to remove any question of validity if the researcher can be seen to be 'too close' to be objective. As explained in chapter 1, the extent of the author's professional practice includes review of secondary data, and anecdotal evidence that an EPG can exists in new building developments. Therefore, it was important to select a relevant case that the author had no prior involvement with at any stage of its design, construction or post-occupancy analysis. The case could then be examined from an independent viewpoint. The analysis is conducted through the expected performance defined in the ES, design stage calculations, and EPI defined in previous research. Therefore, the researcher is independent from the assessment method and performance criteria under examination. Table 7.2 describes the CS criteria of selection.

Table 7.2: Case Study Criteria of Selection

Criteria of Selection	**Justification**	**Selected Case**
An Energy Strategy is available for the case. A document that calculates the energy and CO_2 emissions of a development and proposes measures to reduce these to meet a planning policy reduction target.	These documents are a record of how the designers complied with the planning energy policy and the intended energy and CO_2 emissions performance of the development (see Chapter 2).	An Energy Strategy is available.
Planning achieved and Energy Strategy created after 2004	Energy policies were first introduced in the 2004 version of the London Plan (GLA, 2004).	Planning Approval December 2005
Case located within one of the 32 and City of London Boroughs	Boundary area of the research.	Planning Authority is Southwark
Case is a 'small scale' <500 dwellings	The research is focused on small-scale residential developments,	Domestic Units: 138 Non-domestic floor area:

development and is a predominately residential development >90% of useable floor area	where reports from the GLA have shown an increase in the uptake of HN-CHP (see chapter 2 and 3).	300m2. The non-domestic area is not connected to HN.
The case contains a HN-CHP system as the primary method of energy and CO2 emission reduction.	The technology focus of the research is HN and CHP.	The case study site's heating and hot water demands are meet via a HN containing a CHP and communal gas boilers.
Availability of data	Sufficient data is required in order to provide a detailed analysis of the energy performance and CO2 emissions reduction.	The case has an adequate level of metering and available data for a one year period.

Case Study Introduction and Description

The focus of the study is a residential-led mixed-use building located in the London Borough of Southwark. It was awarded planning approval in December 2005 and final occupation of completion of the occurred in January 2010. The case was identified through a housing association contact upon a request for suitable projects that met the criteria of selection. The author had no prior involvement with the project or any knowledge of the energy performance of the HN-CHP system, it was therefore deemed suitable for use as the case study.

The planning application description (Southwark Planning Department, 2005):

"Erection of building between 8 and 4 storeys in height to provide 138 new dwellings and 300m^2 of commercial space (classes A1, A2, and D1), together with the provision of associated car parking, landscaping, infrastructure works and improvements to existing playground area."

The site is owned by a Housing Association and the construction was procured through a 'design and build' contract. The residential element of the building consists of 138 separate dwellings in a mixture of one to four bedrooms units. The dwellings are arranged over all floors (ground to seventh) with single and multiple exposed facades.

Table 7.3: Case Study Accommodation Schedule

Unit Type	No of Type	Average Floor Area (m^2)
1 bedroom, 2 persons	41	
2 bedroom, 3 persons	8	
2 bedroom, 4 persons	71	
3 bedroom, 5 persons	12	
4 bedroom, 6 persons	6	
Residential Total	**138**	**8,920m^2**
Non Residential Total	**1**	**300m^2**

The non-domestic element of the building is not connected to the site HN-CHP system. Therefore, the non-domestic element of the site does not form part of this case study analysis.

This is a justifiable building for this research as it meets the defined parameters outlined below to ensure a relevant conclusion can be obtained:

Type of Development:

The HN-CHP system serves a residential building within a site boundary area of 13,000m^2 / 1.3 hectares. This is a ratio of 106 units/hectare and thus considered a high density development in an urban environment (*London Plan, 2004*).

Location:

The building is located within the greater London Borough of Southwark and subject to the national planning policy framework, the London Plan and the Southwark local plan policy. Each of these policy frameworks contain energy related policy intent on reducing CO_2 and promoting HN-CHP.

Time Period:

This case was subject to the London Plan (2004) which contained relevant energy policy. The Southwark Local Plan [July 2007] was only in draft form at the time of the submitted application and therefore not adopted policy. However, polices 3.4 (Energy Efficiency) and policy 3.5 (Renewable Energy) were included as part of the planning conditions of the granted application. Therefore, the case was subject to relevant planning policy, planning guidance and a sustainable design standard that are specific to the research.

Building Services and Low or Zero Carbon Technologies:

The thermal demands of the building are served from a HN-CHP system, consisting of a gas-fired CHP and supplemented by three high efficiency gas boilers. There is an electrical energy requirement for the HN system consisting of auxiliary equipment (e.g. pumps).

Thermal distribution to all dwellings is served from three separate piped distribution circuits originating in the energy centre and rising through the building in stair cores 1, 3 and 4. The energy centre and distribution network is located within the demise of the building. Therefore no external characteristics need to be considered. The communal circulation and service areas (bin stores, cycle stores, etc.) of the building are not heated. The commercial units heating and cooling demands are served via air conditioning systems and are not connected to the onsite HN-CHP system; therefore, the thermal energy demands are solely from residential units.

Data Availability:

Available data includes both quantitative and qualitative data sources. Key sources of data that are required and are available include:

- Energy Strategy document – provides the justification of selected technologies and the predicted energy and CO_2 of the thermal demands of the building.
- SAP 2005 Assessment document - the legislative calculation method for predicting energy and CO_2 of the building.
- Utility Meter Data – primary energy consumption, heat and power generation and auxiliary power consumption.

7.3 Evaluation Method

Explicit attention must be given to the design of the study, the process of data collection, the analysis of the data, and the reporting of findings to ensure a CS has validity and reliability (Dooley, 2002). Validity requires the selection of the correct tools or methods that establish a credible line of evidence which can be followed. Furthermore, relating findings back to other evidence (triangulation) or previous literature helps demonstrate validity. Reliability refers to how well the procedures are documented (ibid).

7.3.1 The Data and Collection Method

Quantifiable energy values (kWh) for domestic space heating (SH) and domestic hot water (DHW) consumption is required, these values are derived from:

- The predicted performance defined in the ES document.
- The design SAP 2005 assessment that demonstrated the reduction in CO_2 emissions over Building Regulations compliance.
- The actual metered heat consumption data.

The performance datasets (predicted and measured) are evaluated using the same defined performance indicators (section 7.3.3). These indicators are compared to determine and quantify any observed difference (i.e. '*gap'*) between the datasets.

Predicting the energy performance of the building whether through benchmark figures, calculations, or dynamic computer modelling, can occur at many stages of the design and construction process. The two that are most relevant to this research are:

1) Planning Energy Strategy Report: the document sets out the justification for the methods and technologies adopted to reduce onsite CO_2. This does not include embodied CO_2 of materials or the construction process.

This document is a valid evidence source for predicted energy use and CO_2 as the GLA uses the documents as evidence to evaluate delivered CO_2 reductions.

Although the ES in this CS does not quantify the energy use and CO_2 from specific individual systems (e.g. SH, DHW, lighting, fans and pumps, etc.), it does provide the justification for the technology selection and quantifies the expected CO_2 savings that will be delivered by the selected technologies:

- Development baseline CO_2: 313,799.6 $kgCO_2$/yr
- Savings from onsite HN: 52,515 $kgCO_2$/yr
- Savings from CHP: 28,334 $kgCO_2$/yr

2) Building Regulations Part L - Standard Assessment Procedure 2005 (SAP)

The SAP assessment calculates for an individual dwelling the consumed energy, CO_2, primary energy use and estimated costs of domestic SH and DHW and other regulated energy. SAP assessments are created during detailed design and at completion by a trained and qualified assessor. The SAP follows the *European Energy Performance of Building Directive* methodology for calculating building energy use and CO_2. Output figures are stated for energy in kilowatt hours (kWh) and CO_2 ($kgCO_2$).

The UK Government uses the SAP assessment as evidence of the increased energy performance of newly built dwellings and overall UK housing stock. Existing research literature (see Menezes et al, 2012; Van Dronkelaar et al, 2016) has identified that there is an underlying EPG associated to regulatory models, one of the primary causes being that unregulated energy is not calculated. Furthermore, SAP assessments are not a design tool, they are a regulatory measure to evaluate the performance of a dwelling against a 'notional' dwelling. However, as identified earlier in this research (chapter 2) the GLA dictates that designers must demonstrate CO_2 savings through the SAP methodology. Furthermore, the analysis of ES documents (chapter 6) demonstrated that the SAP is the primary method used in feasibility assessments. Consequently, the GLA policy has resulted in the SAP transforming from a regulatory tool to a defacto design tool. This is supported by Williamson (2012) who identifies that simple calculations tools such as SAP are more likely to be used by designers over more complex design specific modelling software. Van Dronkelaar et al (2016) also argued that the use of regulatory models for design was inevitable due to the dominance of the current regulatory framework in the UK. Therefore, the SAP documents are a valid evidence source as they are the planning policy mechanism and design tool for calculating the CO_2 emissions in new buildings. As this research is solely focused on the energy use and associated CO_2 in the production and delivery of domestic SH and DHW, which are regulated energy, the SAP is a valid source of the predicted energy and CO_2.

The output from the SAP includes a worksheet document, a Part L compliance checklist document and an EPC. These documents provide the relevant information for this research:

- Dwelling Space Heating Requirement (useful): kWh/yr and kgCO_2/yr
- Dwelling Hot Water Heating Output (useful): kWh/yr and kgCO_2/yr
- Energy Used and Generated from Gas Boilers: kWh/yr and kgCO_2/yr
- Energy Used and Generated from CHP: kWh/yr and kgCO_2/yr
- Auxiliary Energy: kWh/yr and kgCO_2/yr
- Distribution Heat Losses – presented as fraction of thermal energy demand.
- Primary Energy: kWh/yr and kgCO_2/yr

The SAP version used in this case study is 2005. All further references to SAP in this chapter are related to the version 2005, unless otherwise stated.

The CS consists of 138 dwellings formed of 27 unit types. A unit is defined as a 'type' if it shares the same footprint area, occupant capacity and architectural general arrangement layout as one or more other dwellings. Units can be of the same type but on different floors. The energy and CO_2 for all dwellings will be summed together to provide the site total. The 138 units are also grouped into their respective unit types to provide the mean demand profile per unit type.

Site Energy Consumption:

The energy use of a building can be observed at a number of levels; total building, individual dwelling, dwelling systems (lighting, heating, etc.), down to individual power outlets (e.g. appliances). The lower the sub-system of data the more complex the monitoring systems become. Typically residential buildings and individual dwellings do not consist of complex monitoring systems beyond dwelling utility metering (water, gas, and electric). Buildings with HNs must now be metered for the heat delivered to the end consumers (Heat Networks Metering and Billing Regulations, 2014).

Buildings with HNs and centralised plant will also have some form of Building Energy Management System (BEMS) which monitors and controls the operation of the central plant equipment. The site has a BEMS but not remote access functionality, therefore data was not available for use in the case study.

The utility meters relevant are gas, electricity and heat generated at building level and heat consumed at a consumer level. Heat meters are provided on the primary side of the each HIU to record the delivered heat to that dwelling. As the HIU is within the boundary of the dwelling (heated space), the total heat losses from HIU's are deemed to be recoverable (BS EN 15316-4-5:2007). Therefore, the heat delivered to the HIU can be taken as the heat consumed or 'useful' heat required. There are bulk heat meters located in the energy centre to each of the three HN distribution circuits to record heat provided to each circuit. These meters are required to calculate the energy loss of the distribution network.

There are statutory utility meters recording total gas (m^3), electricity (kWh) and water (m^3) used in the energy centre; taken in this case study as the 'primary energy consumption' of the HN-CHP system. The energy centre electricity meter records electricity consumed by auxiliary equipment. The CHP has its own heat and electricity meter to record co-generated heat ($kWh_{thermal}$) and power ($kWh_{electrical}$). The gas consumed by the CHP is metered via a gas check meter. The proportion of heat generated from the gas boilers (figure 7.1 'H2') can be stated by subtracting the heat generated from the CHP (figure 7.1 'H1') from the total heat generation meter (figure 7.1 'H3).

All numerical data relating to energy use will be presented in monthly totals for a full calendar year. The year examined represents the period from the 1st June 2014 to the 31st May 2015. Figure 7.1 demonstrate the physical meters that are available.

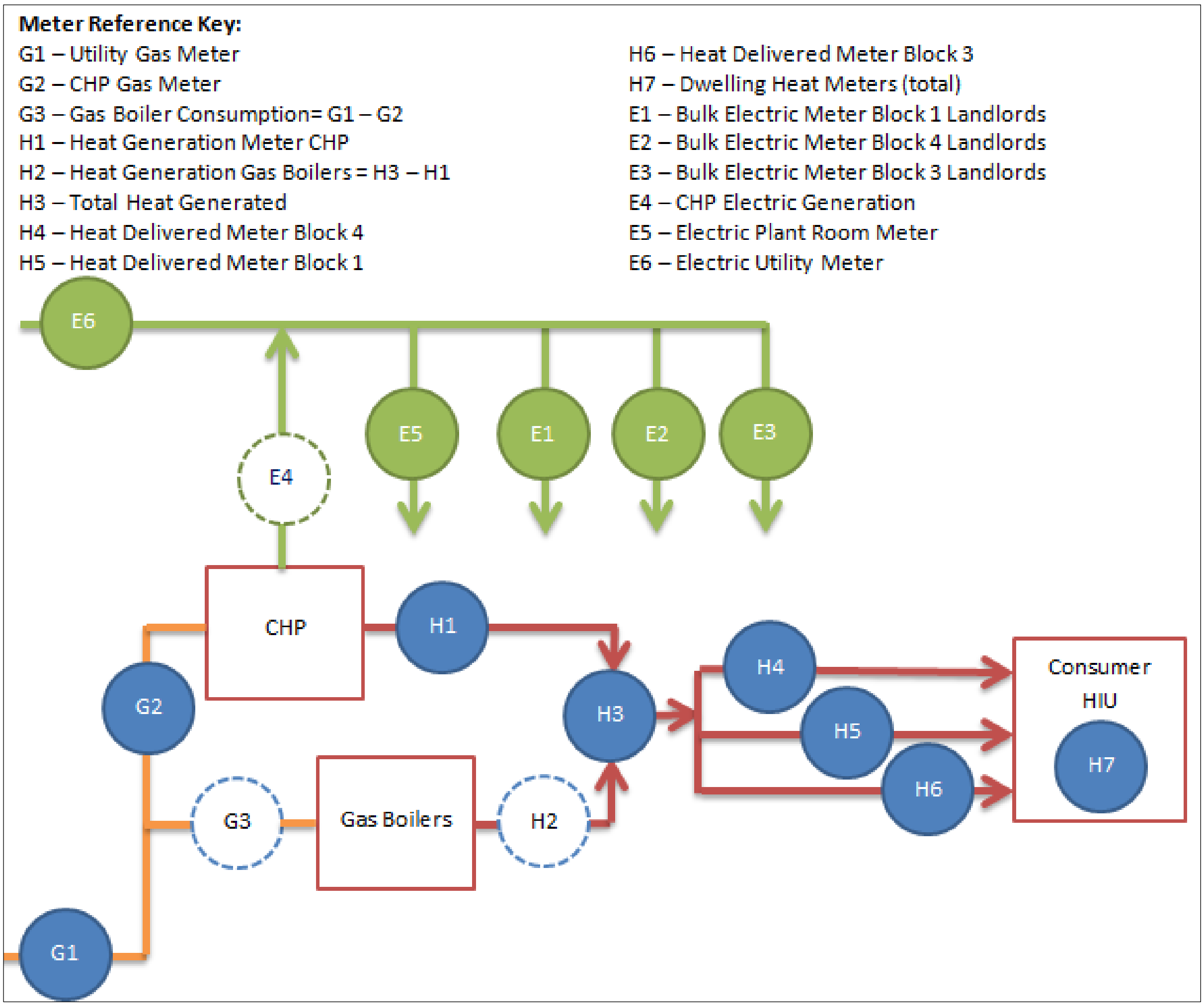


Figure 7.1: Case Study Meter Arrangement Diagram

7.3.2 Technical Evaluation - Energy Performance Indicators

Earlier examination of HN and CHP (chapter 3) identified that HD and LHD are critical energy demand characteristics of these systems. Furthermore, correlation has been shown between LHD and network DHL. However, the analysis of ES documents (chapter 6) identified that the assessment of HN and CHP is based almost solely on the use of SAP assessments and justified mainly through notional concepts of density rather than quantitative assessment (including HD and LHD). This CS analysis will examine the characteristics of HD, LHD and DLF for both the predicted (SAP) and the observed performance in practice. Examination of these values will identify if the assessment of these factors provide a more reasonable expectation of deliverable performance in practice. The equations used to calculate a sites HD, LHD and DLF are defined in equations 1 to 3 as follows:

Equation 1: Heat Density (HD)

$$HD = \frac{Edel}{A}$$

Where:

HD – Heat Density (kWh/m^2.year)

$E_{del:}$ – Energy delivered to the consumers.

A – Area (m^2)

Equation 2: Linear Heat Density (LHD)

$$LHD = \frac{Edel}{HNpl}$$

Where:

LHD – Line Heat Density *(MWh/m/year)*

E_{del} – Energy delivered to the consumers

HN_{pl} – Heat Network Pipe Length (m)

Equation 3: Distribution Loss Factor (DLF)

$$DLF = \frac{Egen}{Edel}$$

Where:

DLF – Distribution Loss Factor

E_{gen} – Total Heat Generated (kWh/year)

E_{del} – Total Heat Delivered (kWh/year)

The EU also provides guidelines to assess the energy performance of a HN based on a Primary Energy Factor (PEF). The PEF is a single parameter of the primary energy consumed to provide heat to the consumers (Werner, 2006; Pacot & Reiter, 2011). This parameter was adopted into the European standard CEN 15316-4-5: 2007.

The Primary Energy Factor (PEF)

Equation 4: Primary Energy Factor (PEF)

$$f_{p,DH} = \frac{\sum_j E_j \cdot f_{p,j} + E_{aux} \cdot f_{p,el} - E_{CHP} \cdot f_{p,el}}{E_{del}}$$

Where:
E_j – the amount of the j[th] primary energy consumed by the network.
$f_{p,j}$ – the primary energy factor of energy source
E_{aux} – auxiliary energy (AE)
E_{CHP} – the amount of electricity generated by the CHP (if installed).
$f_{p,el}$ – the primary energy factor of grid electricity (e.g. power plants)
E_{del} – energy delivered to the consumers.

The PEF also allows the direct comparison of primary energy use between different technologies (e.g. heat networks and individual systems). Pacot et al (2011) identified that the PEF does not evaluate the whole energy use of a HN. The inefficiencies of a HN could be offset by LZC technologies (e.g. CHP) and consequently the potential inefficiencies in the HN are hidden. Three further indicators were defined to assess the performance of a HN (ibid):

1) The Relative Importance of Losses (RiL)

The ratio of consumed energy of the distribution network to the thermal energy delivered to the end consumers. The DHL of the network (E_{loss}) can be stated by the thermal energy leaving the energy centre (E_{gen}) and subtracting the sum of the thermal energy delivered to the consumers (E_{del}).

Equation 5: Relative Importance of Losses (RiL)

$$RiL = \frac{E_{loss} + E_{aux}}{E_{del}}$$

Where:
E_{loss} – Distribution Heat Loss (DHL)
E_{aux} – auxiliary energy (AE)
E_{del} – energy delivered to the consumers.

2) The Primary Energy Efficiency (ε_{DH})

The primary energy efficiency (PEE) considers the benefit of electricity generated by the CHP. It compares the net delivered energy to the primary energy use.

Equation 6: Primary Energy Efficiency (PEE)

$$\varepsilon_{DH} = \frac{E_{del} + E_{CHP} - E_{aux}}{\sum_{j} E_j \cdot f_{p,j}}$$

Where:
E_{del} – energy delivered to the consumers.
E_{CHP} – the amount of electricity generated by the CHP (if installed).
E_{aux} – auxiliary energy (AE).
E_j – the amount of the j^{th} primary energy consumed by the HN.
$f_{p,j}$ – the primary energy factor of energy source.

3) The District Heating Global Efficiency, η_{DH}

A general definition of a HN's efficiency. The ratio between all of the energies delivered and all the necessary energy.

Equation 7: District Heating Global Efficiency (DHGE)

$$\eta_{DH} = \frac{E_{del} + E_{CHP}}{\sum_{j} E_j + E_{aux}}$$

Where:
E_{del} – energy delivered to the consumers.
E_{CHP} – the amount of electricity generated by the CHP (if installed).
E_{aux} – auxiliary energy (AE).
E_j – the amount of the j^{th} primary energy consumed by the HN.

Summary of Energy Performance Indicators

The performance of the HN-CHP system are next analysed using the defined EPI outlined. Values for each EPI will be evaluated using both the predicted (SAP) and observed energy consumption of the HN and CHP to determine the existence and scale of the EPG.

7.3.3 Direct Performance Comparison – Heat Network and Gas Boilers

The examination of the ES document offers a unique perspective of the CS compared to traditional POE that typically only consider quantitative performance values (kWh, $kgCO_2$, %)

and/or qualitative data (occupant experiences). The ES provides the designers assessment and justification for the adoption of a HN and CHP. Therefore, it is relevant to review both the quantitative valves and also the professional opinions (written justifications) specific to the technology performance. By examining both it is possible to review the accuracy of the calculations (in terms of energy and CO_2), but also the appropriateness of the professional perspectives that underline those quantitative values.

The ES stated that the predicted CO_2 saving per year from the installation and operation of the HN and CHP would be 52.5 and 28.3 TonnesCO_2/year respectively. The calculation method of primary energy figures is not stated. Therefore, the ES figures can only be assessed with a direct comparison.

The ES document states:

"The advantages of this type of system [Heat Network] *is that it is generally more efficient than individual boilers (smaller diversified load with modular boilers working at most efficient load)"*

The designer's stated justification for adopting a HN was the increased thermal generation efficiency of larger centralised boilers over individual domestic gas boilers. This is representative of the justifications presented in the sample of ES examined in chapter 6. The savings are quantified as:

"Calculated carbon savings of 17% could be realised with a district heating [Heat Network] *scheme if high efficiency boilers are installed, sized and controlled to work at maximum efficiency (approximately 94%).*

*The provision of district heating will result in an additional **17% carbon saving** or **52.515 tonnes of CO_2**."*

Therefore, there are two performance criteria to evaluate the justification of HN technology:

1) What is the thermal generation efficiency of the energy centre gas boilers? The predicted thermal efficiency is 94%.

2) Does the HN system provide a CO_2 saving of 52,515 kgCO_2/yr over theoretical domestic gas boiler systems?

The thermal generation efficiency of the gas boilers can be calculated by modifying equation 7 to account for the gas boilers only (equation 8). The CHP energy generation will be removed from the equation and only primary energy consumed and heat generated by the gas boilers will be used. AE (E_{aux}) will also be discounted as this is related to energy consumed by the HN.

The energy centre consists of three gas boilers. There is no individual gas or heat meters installed on the gas boilers. Therefore, the boilers will be treated as a single system with an overall thermal efficiency. The primary energy input ($E_{j,boilers}$) of the boilers will be the remaining gas volume (m^3) after subtracting the CHP consumption ($E_{j,CHP}$). The heat generation of the gas boilers ($E_{gen,boilers}$) is the sum of thermal energy leaving the heating plant after subtracting the CHP thermal generation ($E_{gen,CHP}$). All thermal losses associated with pipework, pumps, valves, etc. within the energy centre to the bulk heat meter (meter reference *H3* in figure 7.1) will be included within boiler efficiency calculation.

Equation 8: Gas Boiler Thermal Efficiency

$$\eta \text{Boilers} = \frac{\text{Egen, boilers}}{\text{Ej, boilers}}$$

Where:

$\eta_{Gas\ Boilers}$ – thermal efficiency of gas boilers (%).

$E_{gen,boilers}$ – heat generated from gas boilers (kWh).

$E_{j,boilers}$ – the amount of the j^{th} primary energy consumed by the boilers (kWh).

Determining the CO_2 saving of a HN over individual boiler systems requires the boundary of each system to be identified. The HN comprises of several components (e.g. multiple heat generators, distribution network and consumer HIUs), whereas individual domestic gas boilers consume and generate energy at the point of use. The difference in the two systems is illustrated in figure 7.2.

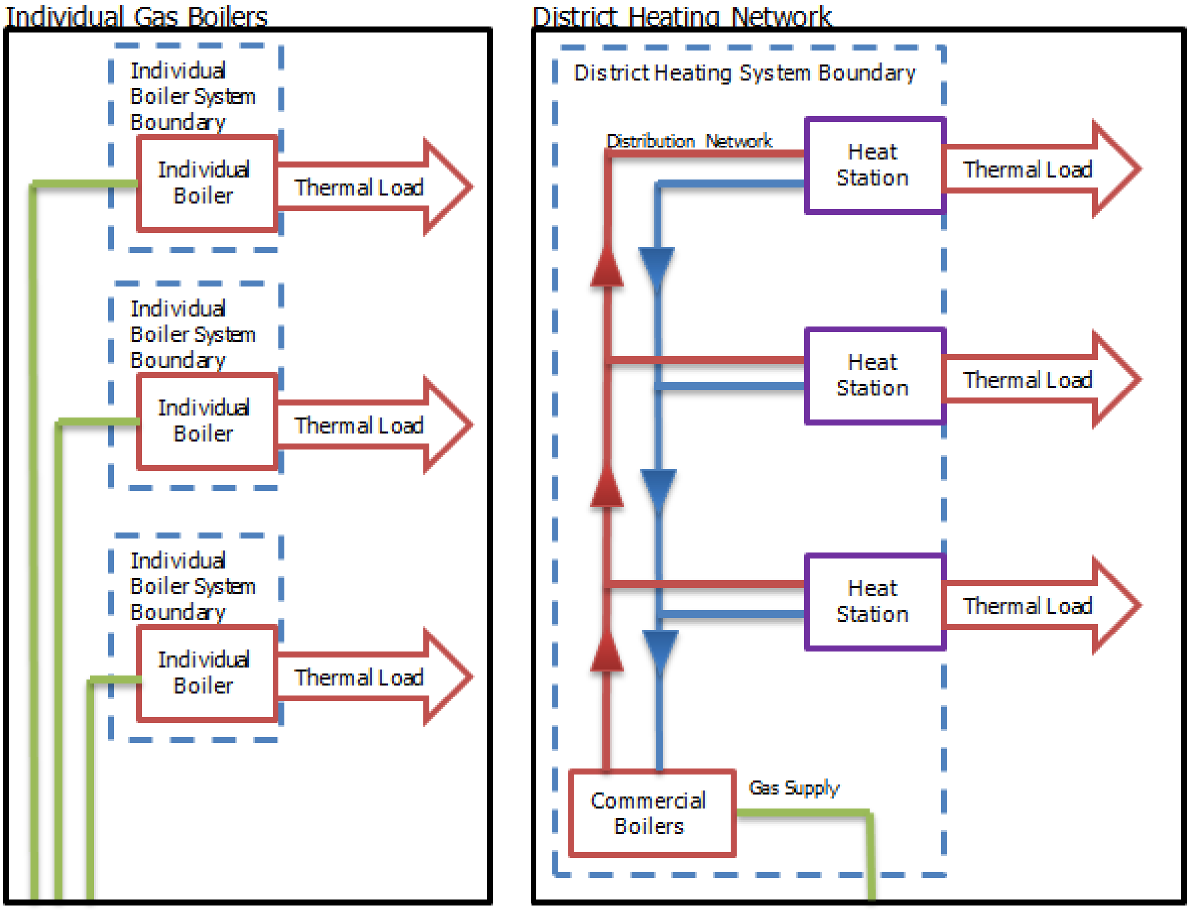


Figure 7.2: System Boundaries of Individual Gas Boilers and a Heat Network

The efficiency of the individual domestic gas boilers is defined by equation 9. A range of domestic gas boiler efficiencies will be evaluated based on the SAP 2005 *table 4b* default values. A POE of in-situ condensing boilers found a mean efficiency of 82.5% (EST, 2009). Therefore, the SAP boiler efficiency range provides a reasonable reflection of domestic gas boilers performance in practice.

Equation 9: Domestic Gas Boiler Energy Consumption

$$Ej, domestic = \frac{Edel}{Boiler\ Efficiency\ (\%)}$$

Where:
E_{del} – energy delivered to the consumers.
Boiler Efficiency - SAP 2005 Table 4b:

Boiler Type and Control		Efficiency (%)
A	Non-condensing combi with automatic ignition	73
B	Condensing combi with automatic ignition	83
C	Non-condensing combi with permanent pilot light	69
D	Condensing combi with permanent pilot light	79

The ES calculated the CO_2 savings from the HN separately to the CHP savings. Therefore, the CHP will be discounted from HN efficiency evaluation. As a HN is related to the generation and distribution of heat only, the electrical generation from the CHP is also discounted. The ES does not state if CO_2 savings include network DHL (E_{loss}). As illustrated in figure 7.2, the boundary of a HN system includes the distribution network, therefore losses must be included in the energy balance of a HN system. CIBSE (2013) design guidance *'AM12: Combined Heat and Power for Buildings',* defines an equation for calculating the performance of a HN without a CHP. This is given in equation 10.

Equation 10: HN CO_2 Emissions without CHP

$$CO2\ Emissions\ \mathbf{without}\ CHP = \left[\left(\frac{Egen}{\eta boiler}\right).Ef,boiler\right] + [Eaux\ .Ef,elec]$$

Where:
E_{gen} – Total thermal energy generation.
η_{boiler} - Efficiency of gas boilers.
$E_{f,boiler}$ – Emission factor of boiler fuel.
E_{aux} – Auxiliary energy (AE)
$E_{f,elec}$ – Emission factor for electricity.

7.3.4 Direct Performance Comparison – CHP

The ES states the following in justification of adopting a CHP:

"The inclusion of this technology [CHP] *will still give an additional* ***9% carbon saving*** *or* ***28.334 tonnes of CO_2****."*

Therefore, the specific elements to evaluate are the two performance criteria defined by ES:

1) Does the CHP reduce the CO_2 compared to a HN without CHP and what is the potential saving in percentage reduction? The predicted reduction is 9%.

2) What is the value of $kgCO_2$ savings attributable to the CHP? The predicted saving is 28.3 tonnes of CO_2.

The CHP servicing company issued a monthly *Declaration of Performance*. The declaration provides the primary energy consumption (kWh), heat and electricity energy generation (kWh) of the CHP. The CO_2 savings of the HN-CHP system can be calculated using the defined equations from *'AM12'* (CIBSE, 2013) (equation 11). The predicted performance of the gas boiler efficiency (%) is taken to be 94% in line with the performance stated in the ES. For the observed performance in practice the gas boiler efficiency (%) will be taken as measured (equation 8).

Equation 11: HN-CHP CO_2 Emissions

$$CO2\ \textbf{with}\ CHP = \left[\left(\frac{Egen - Egen, CHP}{\eta boiler}\right) . Ef, boiler\right] + (Ej, chp\ . Ef, chp) + [(Eaux - Echp). Ef, elec]$$

Where,

E_{gen} – Total thermal energy generation.
η_{boiler} - Efficiency of gas boilers.
$E_{f,boiler}$ – Emission factor of boiler fuel.
E_{aux} – Auxiliary energy (AE)
$E_{f,elec}$ – Emission factor for electricity.
$E_{gen,CHP}$ - Thermal energy supplied from CHP.
E_{CHP} - Electrical energy supplied from CHP.
$E_{j,CHP}$ – Primary energy consumption of the CHP.
$E_{f,CHP}$ - Emission factor of CHP fuel.

7.3.5 Assumptions and Limitations

There are several limitations and assumptions that must be made in order to complete the POE. Firstly, as real world meter readings are used, there is the potential of erroneous data created by missing values or extreme data outliers. Burzynski et al (2012), dealt with missing values by correcting through linear interpolation of the complete values. The heat consumption readings used are taken directly from fiscal meters used to bill residents. These meters are subject to EU and UK regulations and therefore can be expected to provide a high level of accuracy.

Secondly, examination of regulatory compliance assessments (SAP) has identified that inaccuracies can exist (UCL, 2014). The regulatory assessments undertaken for the CS were completed by a qualified assessor and therefore an appropriate level of expertise and accuracy can reasonably be expected. Part of this analysis is to investigate some of the potential inadequacy of these compliance assessments to predict performance in practice (DLF and AE).

Finally, the CS is limited to the energy and CO_2 of the HN-CHP system in comparison to the design intent. The study does not seek to investigate the wider implications of building energy performance that is explored in other available studies, for example occupant behavior (see Delzendeh et al, 2017) or design versus construction (see Johnston et al, 2015).

7.4 The Case Study

7.4.1 Analysis of Predicted Performance – The Energy Strategy

The defined EPI (section 7.3.2) cannot be applied to the ES as it does not quantify the energy use and CO_2 from the individual systems (i.e. primary energy used, energy delivered, DHL, AE, etc.). The ES does provide quantified CO_2 savings that were predicted to be achieved by the implementation of the selected technologies. Therefore, a direct comparison will be made between the ES stated reductions and reductions achieved in practice. A copy of the Energy Strategy is included in appendix 5.

- CO_2 savings from HN: 52,515 $kgCO_2$/yr
- CO_2 savings from CHP: 28,334 $kgCO_2$/yr

7.4.2 Analysis of Predicted Performance – The SAP

The output from the SAP includes a worksheet that provides the estimated energy consumption and CO_2 specific to each dwelling. Figure 7.3 provides an example of a section of the worksheet. Each dwelling has an individual SAP worksheet. The relevant figures from all worksheets are included in Appendix 2.

	Energy kWh/year		**Emission factor** kg CO_2 /kWh		**Emission** kg CO_2/year	
Water heated by CHP or recovered heat from power station:	125.88	×	box (107*)	=	7.84	(108*)
Energy for water heated by CHP or recovered heat from power stations = (87a)*						
Efficiency of community boilers % *use actual efficiency if known, or value in Table 4a*	93.00 (109*)					
Water heated by boilers: (87b*) x 100 ÷ (109*) =	3248.46	×	0.19	Table 12 =	630.20	(110*)
If water heated by immersion heater, box (51)	2997.09	×	0.000	Table 12 =	0.00	(111*)
Space heating from CHP or recovered heat, box (86*)	160.84	×	box (107*)	=	10.02	(112*)
Space heating from boilers (87*) x 100 ÷ (109*) =	4,150.61	×	0.19	Table 12 =	805.22	(113*)
Electricity for pumps and fans, box (88*)	0.00	×	0.422	Table 12 =	0.00	(114*)

Figure 7.3: Example Section of a SAP Worksheet

7.4.2.1 Space Heating Correction Factor for Reference Year

The SAP 2005 calculates the useful energy requirement for SH based on degree-days and the heat loss coefficient. This quantity is known as the dwelling's annual SH requirement and is calculated in SAP worksheet box 81:

> SAP Box 81:
> *SH requirement (kWh/yr) = 0.024 x Heat Loss Coefficient (SAP box 37) x Degree Days*

Degree-days are dependent on 'base' temperature which is calculated by adjusting the mean internal temperature to take account of heat gains. Degree-days for different base temperatures are given in Table 10 of the SAP Technical Manual, using linear interpolation for intermediate values (2005). The degree-days for the reference year (June 2014 to May 2015) were obtained from an online database (*degreedays.net,* accessed 24.11.15*).* The number of actual degree days was approximately 40% less than the SAP standard values (table 7.4). Therefore, the SAP prediction for SH requirement was corrected to reflect the degree-days of the reference year.

Table 7.4: Difference in Degree Days for SAP and Actual in Reference Year

Base Temperature (^{o}C)	**SAP Degree-Days**	**Reference Year Degree-Days**	**Difference (%)**
9.50	860	456	-46.98
10.00	950	526	-44.63
10.50	1045	598	-42.78
11.00	1140	677	-40.61
11.50	1240	759	-38.79
12.00	1345	845	-37.17
12.50	1450	938	-35.31

Correcting the baseline SAP data for the reference year degree days, provides the corrected SAP (SAP*) SH requirement (table 7.5).

Table 7.5: SAP and SAP* Space Heating Requirement

Space Heating Requirement		
Units:	**SAP**	**SAP***
kWh/year	331,054	196,242
kWh/m^2/year	37.12	22.00

*Corrected for degree-days

The dwellings were assigned into groups based on their prospective 'type' (floor area and occupancy). The mean SH energy consumption for each type was taken. The results demonstrate that there was a range of 37% to 44% difference between the SAP and SAP* (*corrected for degree days) figures (table 7.6). The overall reduction in site domestic SH demand was found to be 40%, reflecting the reduction in degree-days.

Table 7.6: SAP and SAP* Unit Type Space Heating Requirement

Unit Type	Space Heating Requirement				Difference
	SAP	SAP*	SAP	SAP*	
	kWh/year	kWh/year	kWh/m^2	kWh/m^2	%
T1	3,944	2,493	46.95	29.68	37%
T2	1,954	1,163	42.47	25.28	40%
T3	2,132	1,301	45.36	27.69	39%
T4	2,865	1,785	46.98	29.26	38%
T5	2,274	1,372	36.68	22.13	40%
T6	2,613	1,620	45.05	27.94	38%
T7	2,398	1,449	36.89	22.29	40%
T8	2,060	1,182	31.69	18.19	43%
T9	2,596	1,557	40.57	24.33	40%
T10	3,280	1,979	48.23	29.10	40%
T11	2,282	1,328	34.06	19.82	42%
T13	2,053	1,197	30.64	17.87	42%
T14	2,146	1,241	31.10	17.98	42%
T15	2,487	1,472	36.05	21.33	41%
T16	2,135	1,192	28.47	15.89	44%
T18	2,627	1,491	32.04	18.18	43%
T19	3,350	2,022	38.51	23.25	40%
T20	3,938	2,332	34.24	20.28	41%
T21	4,661	2,896	47.08	29.25	38%
T22	3,365	2,016	48.77	29.22	40%
T23	3,770	2,330	43.84	27.10	38%
T24	1,956	1,089	29.20	16.25	44%
T25	2,551	1,504	38.08	22.44	41%
T26	3,151	1,884	48.48	28.99	40%
T27	1,827	1,076	39.71	23.40	41%
T28	1,827	1,076	39.71	23.40	41%
T30	1,825	1,016	27.25	15.16	44%

*Corrected for degree-days

7.4.2.2 Total Domestic Thermal Energy Requirement

The total thermal energy requirement for each dwelling is the sum of SH (kWh/year) and DHW (kWh/year). The SAP bases the energy requirement for DHW on the estimated occupancy levels and a predicted hot water usage per person (SAP box 51). The energy for DWH cannot be corrected as the actual occupancy levels were not known. The total thermal requirement relates to the energy delivered (E_{del}). Refer to table 7.7 in section 7.4.2.7 for the results.

7.4.2.3 Thermal Energy Balance – Gas Boilers

The CHP and gas boilers each provide a proportion of the total thermal energy load. The SAP calculates the proportion in box 84*:

> SAP Box 84*:
> *Gas Boiler Thermal Energy Generated = Thermal energy requirement (useful) x fraction of heat from boilers x 100] / overall system efficiency x distribution loss factor.*

The fraction of heat is defined by the designer and manually added into the SAP. The fraction from the gas boilers in this CS has been stated as 0.96 (out of 1.0). The overall system efficiency is selected by the SAP assessor from a range of default values in *table 4c* (2005; p.148) and in this case is 100%. The DLF in this case has been assessed to be between 1.05 (5%) and 1.10 (10%), averaging 1.09 (9%) (SAP box 85*).

The thermal energy generated by the gas boilers has been calculated for the SAP and corrected SAP*. The SAP* predicts a reduction in the energy produced by the gas boilers, owing to the reduced SH demand (see table 7.7 in section 7.4.2.7).

The primary energy consumption related to domestic SH and DWH is a function of the energy generated and the generation efficiency. The SAP calculates the thermal primary energy consumption by SAP box 82*.

> SAP Box 82*:
> *Primary Energy consumption Gas Boilers ($E_{j,boilers}$) = [boiler thermal generation x 100] / boiler thermal efficiency.*

The thermal energy generated by the gas boilers is presented in table 7.7. The SAP*calculates a reduction in the total energy produced by the gas boilers owing to the reduced SH demand.

7.4.2.4 Thermal and Electrical Energy Balance – CHP

The fraction of heat provided by the gas boilers has been determined by the designer to be 0.96. Therefore, the CHP heat fraction is 0.04. The SAP calculates the thermal energy generated by the CHP by the SAP equation box 83*:

SAP Box 83*:
CHP Thermal Energy Generated = Thermal energy requirement (useful) x fraction of heat from CHP x 100] / overall system efficiency x distribution loss factor.

The thermal energy generated by the CHP is presented in table 7.7. The SAP* calculated reduction in the energy produced by the CHP in the reference year, again owing to the reduction in SH demand.

The SAP worksheet does not calculate the electrical generation of the CHP. The heat-to-power ratio is stated in the worksheet (Box 106*) and has been applied to calculate the CHP electrical energy generation (table 7.7). The CHP electrical energy generation relates to value E_{CHP} for the EPI.
The amount of the primary energy consumed by the CHP ($E_{j,CHP}$) is not calculated within the SAP assessment. The CHP primary energy is included in the CO_2 factor for heat (SAP box 107*). The CHP primary energy is required to determine the total amount of the primary energy consumed by the HN-CHP (*Ej*). The thermal and electrical efficiencies of the CHP are given in boxes 101* and 102* respectively. Therefore, the primary energy consumption of the CHP can be calculated from equation 12. The results are presented in table 7.7. The CHP represents 8.5% of the total primary energy usage (SAP*).

Equation 12: CHP Primary Energy Consumption

$$Ej, CHP = \left[\left(\frac{Egen, CHP \,.\, 100}{\eta\mathrm{CHPthermal}}\right)\right]$$

Where,
$E_{j,CHP}$ – Primary energy consumption of the CHP.
$E_{gen,CHP}$ – CHP thermal energy generation.
$\eta_{CHPthermal}$ – CHP thermal efficiency.

7.4.2.5 Total Primary Energy Consumption (Ej)

The total primary energy consumed by the HN-CHP system (*Ej*) is the sum of the all the primary energies (gas and electricity) consumed by all heat generating technologies. The results are presented in table 7.7 in section 7.4.2.7.

7.4.2.6 Distribution Heat Loss (E_{loss}) and Auxiliary Energy Consumption (E_{aux})

The SAP worksheet calculates DHL from a defined distribution loss factor (DLF). The average DLF for the CS was 1.09 (9%). For SAP*, the DLF is applied to the energy delivered (E_{del}).

The SAP worksheet calculates AE as a predefined value related to the type of heating systems selected. The SAP assessment allocated zero (0.00 kWh/year) energy consumption for AE (box 88*). This is evidently not a reflection of the performance in practice. Therefore, for the corrected SAP* a value of 1% of delivered thermal energy (E_{del}) has been taken for AE (E_{loss}). This is consistent with the SAP 2012 design assessment procedure (SAP, 2012: C3.2): *"CO_2 emissions associated with the electricity used for pumping water through the distribution system are allowed for by adding electrical energy equal to 1% of the energy required for space and water heating."*

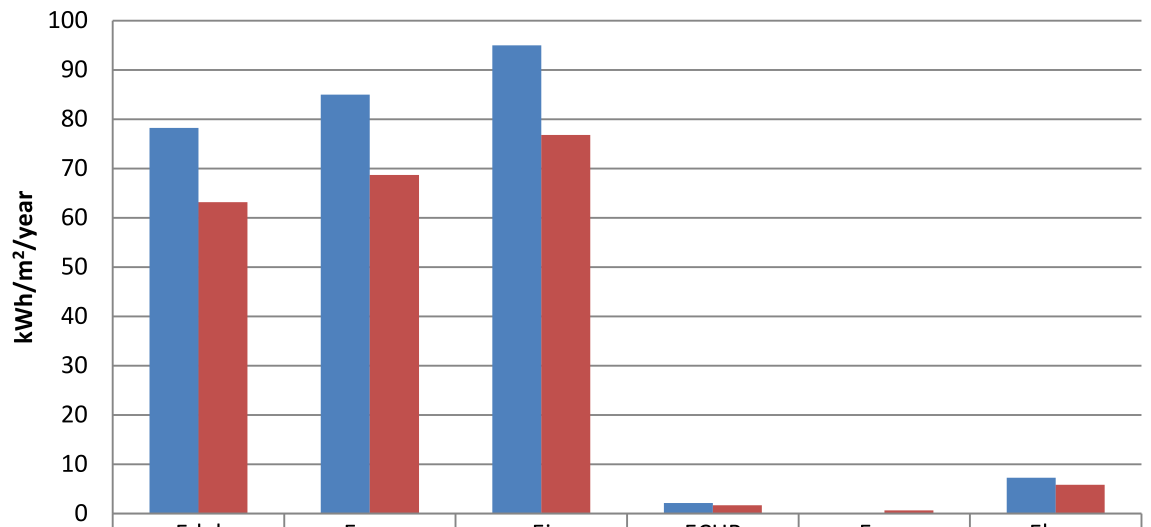
7.4.2.7 Summary of Energy Figures

Through investigation of the SAP assessment worksheet documents and calculation producers, the relevant energy performance figures have been identified. Table 7.7 and figure 7.4 demonstrates the key figures that have been determined to allow evaluation against the observed performance in practice.

Table 7.7: Summary of SAP and SAP* Results

Summary of SAP and SAP* Results			
Energy Performance Figure:	**Units:**	**SAP**	**SAP***
Total Energy Delivered (E_{del})	kWh/year	697,896	563,083
	kWh/m^2/year	78.24	63.13
Gas Boilers Thermal Energy Generation ($E_{gen,boilers}$)	kWh/year	727,184	588,138
	kWh/m^2/year	81.53	65.94
Gas Boilers Primary Energy Consumption ($E_{j,boilers}$)	kWh/year	781,918	632,406
	kWh/m^2/year	87.66	70.90
CHP Thermal Energy Generation per Year ($E_{gen,CHP}$)	kWh/year	30,606	24702
	kWh/m^2/year	3.43	2.77
CHP Electrical Energy Generation (E_{CHP})	kWh/year	18,893	15,248
	kWh/m^2/year	2.12	1.71
CHP Primary Energy Consumption ($E_{j,CHP}$)	kWh/year	65,120	52,577
	kWh/m^2/year	7.30	5.89
Total Primary Energy Consumption (E_j)	kWh/year	847,037	684,963
	kWh/m^2/year	94.96	76.79
Distribution Heat Loss (E_{loss})	kWh/year	64,549	52,110
	kWh/m^2/year	7.24	5.84
Auxiliary Energy (E_{aux})	kWh/year	0.00	5,631
	kWh/m^2/year	0.00	0.63

*Corrected for degree-days



	Edel	Egen	Ej	ECHP	Eaux	Eloss
SAP	78.24	84.96	94.96	2.12	0	7.24
SAP*	63.13	68.71	76.79	1.71	0.63	5.84

Figure 7.4: SAP and SAP* Summary of Energy Figures

7.4.3 Analysis of Actual Performance in Practice

The energy performance of the HN-CHP system is analysed using the utility energy meters. The meter readings are presented as monthly totals, with the readings taken on the final day of each month. Results are presented as a total consumption for the building over the reference year (kWh/year) and total energy consumption per square metre of heated floor area (kWh/m^2).

7.4.3.1 Total Primary Energy Consumption (Ej)

The primary energy fuel is natural gas. The utility gas meter provides fuel consumption by volume in cubic meters (m^3). The volume of gas can be converted into energy (kWh) by the calculation defined in the *'The gas (Calculation of Thermal Energy) Regulations (SI 1996/439)',* and given here as equation 13:

Equation 13: Gas Consumption

$$Gas\ (kWh) = \left[\left(\frac{Volume\ (m3).CV.1.02264}{3.6}\right)\right]$$

Where,

CV – Calorific Value

The Calorific Value (CV) is a measure of energy contained in a fuel. The CV refers to the energy released when a known volume of gas is completely combusted under a standard temperature (15^{o}C) and pressure (1013.25 millibars) (National Grid, 2018). The CV is expressed as Mega-joules per cubic meter (MJ/m^3). A daily average CV for each charging area (related to postal code) is provided by the 'National Grid', these daily averages are published at *http://www2.nationalgrid.com*. The average daily CV for the monitoring period for the CS charging area is provided in table 7.8. Table 7.9 presents the resultant primary energy consumed (*Ej*) by the HN-CHP system.

Table 7.8: Average Calorific Value and the Resultant Energy Available per m^3 Natural Gas

Average CV during Monitoring Period											
2014							2015				
Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
39.15	39.25	39.08	39.23	39.17	39.09	39.03	38.95	39.00	38.87	39.17	39.26
kWh/nm^3											
11.12	11.15	11.10	11.15	11.13	11.10	11.09	11.07	11.08	11.04	11.13	11.15

Table 7.9: Primary Energy Consumption

Primary Energy Consumption (E_j)			
Month	**Gas Volume Consumption (m^3)**	**Energy Consumption (kWh)**	**Energy Consumption (kWh/m^2)**
June 2014	9,107	101,160	11.34
July 2014	8,501	94,783	10.63
August 2014	7,132	79,171	8.88
September 2014	5,830	64,977	7.28
October 2014	9,514	105,862	11.87
November 2014	12,125	134,632	15.09
December 2014	15,778	174,910	19.61
January 2015	16,524	182,847	20.50
February 2015	15,447	171,131	19.19
March 2015	13,897	153,427	17.20
April 2015	9,114	101,398	11.37
May 2015	9,353	104,298	11.69
Total	**132,322**	**1,468,596**	**164.64**

7.4.3.2 Total Thermal Energy Generation (E_{gen})

The total heat generated is recorded by the bulk heat meter (HM) in the energy centre (table 7.10). Refer to meter reference 'H3' from figure 7.1.

Table 7.10: Primary Thermal Energy Generated

Total Thermal Energy Generation (E_{gen})		
Month	**kWh**	**kWh/m^2**
June 2014	61,200	6.86
July 2014	54,300	6.09
August 2014	56,300	6.31
September 2014	56,800	6.37
October 2014	73,600	8.25
November 2014	91,600	10.27
December 2014	127,600	14.30
January 2015	138,600	15.54
February 2015	129,500	14.52
March 2015	121,800	13.65
April 2015	90,800	10.18
May 2015	80,400	9.01
Total	**1,082,500**	**121.36**

7.4.3.3 Delivered Thermal Energy (E_{del})

The total thermal energy delivered to the consumers (E_{del}) is the sum of the all 138 domestic HMs. Figure 7.4 demonstrates the wide variance in average annual consumption across the different and similar unit types. Figure 7.5 demonstrates the HMs with the minimum, mean and maximum consumption for each month. Also a typical annual domestic demand curve can be observed, where demand increases through the winter months and drops during the summer months.

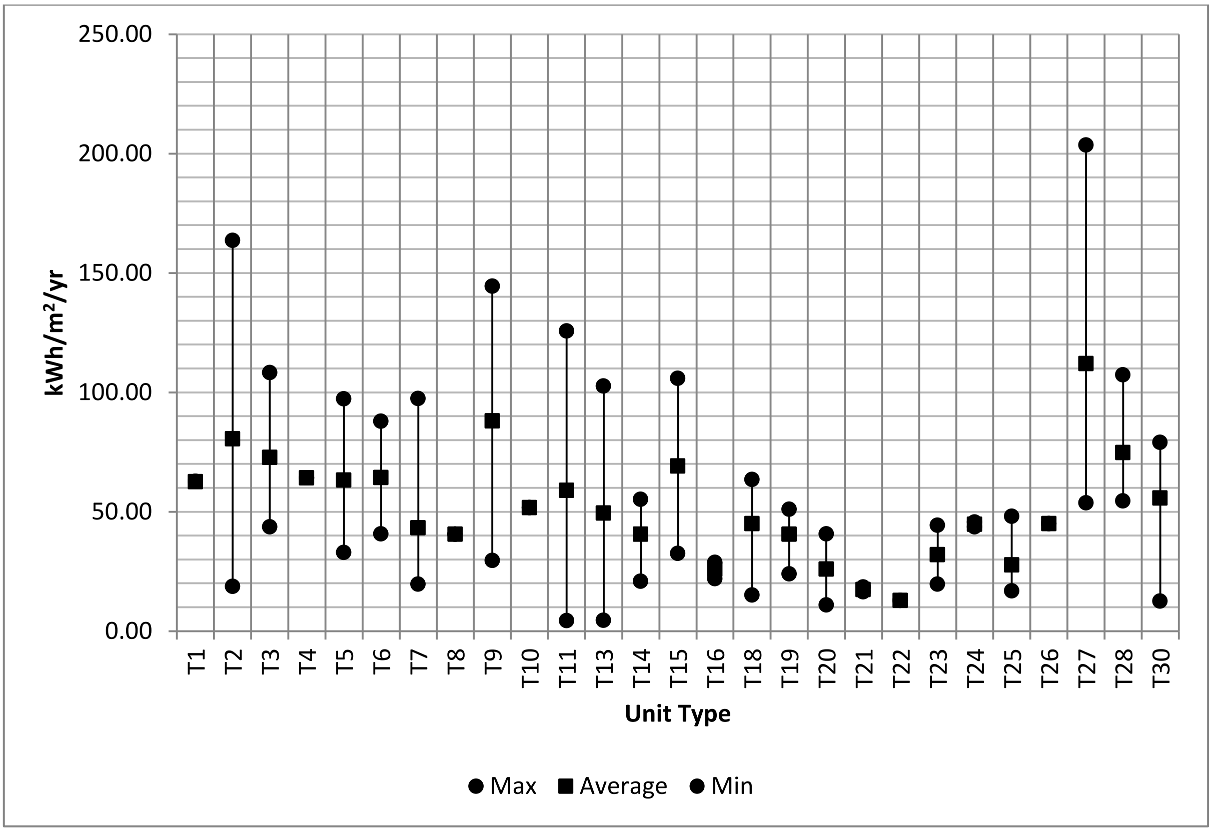


Figure 7.5: Annual Heat Consumption by Unit Type

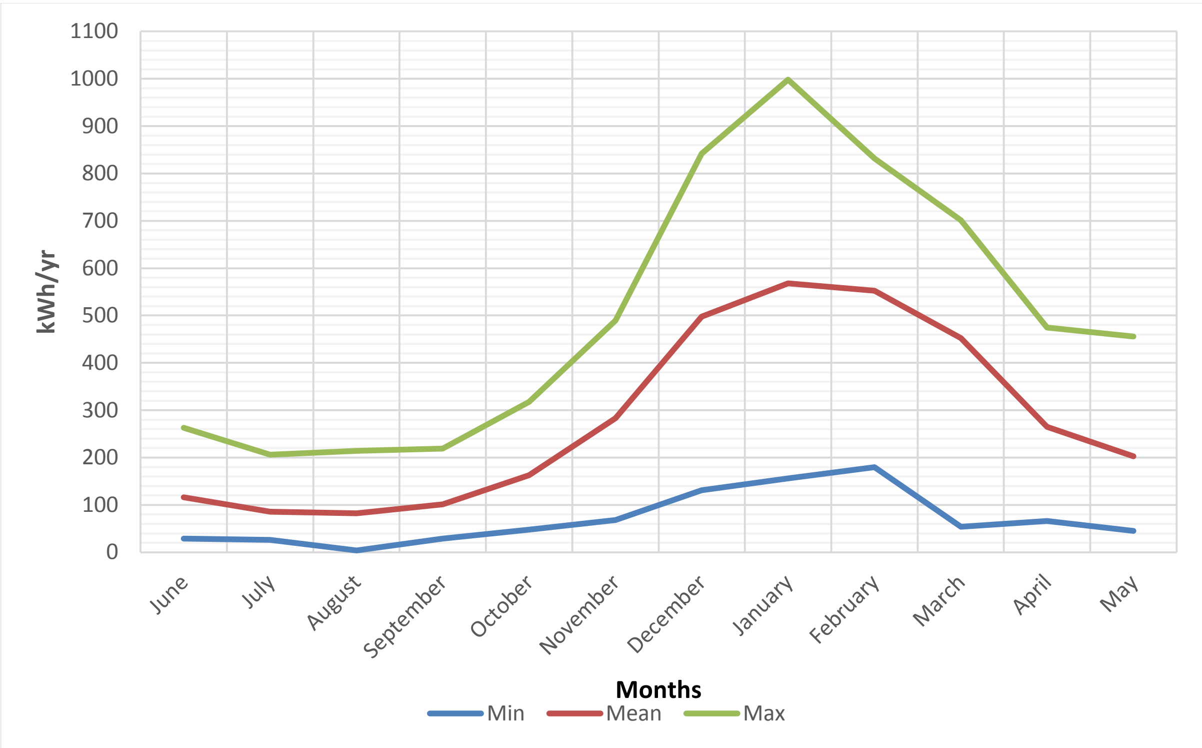


Figure 7.6: The Range (Min, Mean, Max) of Domestic Heat Consumption per Month

There were sixteen HM readings of zero consumption. A zero reading indicates either an unoccupied period or potentially a meter reading error. An error can relate to a misreading or miscommunication with the HM. According to the building lease records, one dwelling (plot 24) is known to have been unoccupied between August 2014 and the end of the monitoring period (9 months). Therefore, plot 24's total consumption (842 kWh/year) represents the lower limit to identify other potential erroneous meter data. Burzynski et al (2012) study used a HM lower limit of 10 kWh per week ~ 520 kWh/year. It is possible for an occupied dwelling to consume heat, for example, facility managers can leave SH on at a low temperature to prevent damp or condensation.

Examining all of the domestic HM data, it was found that 11 HMs recorded below 842kWh/year. Examination of the data provides three patterns of consumption which have been arranged into groups as follows (table 7.11):

- Group 1: Plot 24 - known unoccupied period.
- Group 2: Plots 21, 43, 94 & 132 - these plots demonstrate the typical monthly demand curve, so are deemed to be just low heat consumers. No adjustment to readings will be made.
- Group 3: Plots 13, 36, 48, 62, 68 & 112 - these plots demonstrate a very low (<10kWh) and/or zero meter reading over several months, and/or did not present a standard demand curve. This are deemed to present abnormal data, readings will be corrected by the average readings for each plots corresponding unit type.

Table 7.11: Domestic Heat Meters with Abnormally Low Readings

Low Heat Meter Reading Heat Stations												
-	2014							2015				
Plot	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Group 1												
24	365	278	131	28	21	10	9	0	0	0	0	0
Group 2												
21	24	36	25	42	43	71	76	107	147	102	78	108
43	17	19	17	27	18	19	24	23	27	54	28	30
94	29	26	21	29	83	68	131	156	180	54	66	45
132	15	23	22	22	25	22	31	38	28	26	20	21
Group 3												
13	9	7	10	10	11	12	9	17	23	12	11	8
36	17	12	15	7	10	21	112	163	150	85	38	9
48	13	0	0	6	0	33	74	105	112	109	25	22
62	81	86	86	79	21	0	0	0	0	0	13	80
68	5	5	9	9	14	50	163	167	145	75	47	7
112	3	2	1	2	4	0	13	18	14	3	5	2

From the remaining 127, one other HM recorded a zero monthly reading, this has been defined as group 4. The two months with a zero consumption reading were corrected through linear interpolation of the previous and following months (table 7.12) (Burzynski et al, 2012).

Table 7.12: Group 4 Heat Meter Readings

Heat Station Heat Meter Readings												
-	2014							2015				
Plot (Type)	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Group 4												
96 (T7)	50	37	39	43	59	233	548	467	0	420	23	0

The six domestic HM that have been identified to present abnormal meter readings have been identified as group 3. The group 3 meter readings have been corrected to the average monthly meter readings of their respective dwelling types. As type 4 only consists of one dwelling the readings were corrected to type 5, which is approximately the same floor area ($62m^2$) and same occupancy size (2 bedroom, 3 persons). Table 7.13 shows the corrected readings for Group 3 and 4.

Table 7.13: Group 3 and 4 Corrected Heat Meter Readings

Group 3 & 4 Corrected Heat Meter Readings												
-	2014							2015				
Plot (Type)	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Group 3												
13 (T4)	91	61	84	89	201	379	584	693	656	571	273	226
36 (T2)	114	90	79	96	160	317	544	647	613	503	324	227
48 (T28)	103	94	77	122	219	356	515	556	562	384	250	195
62 (T16)	78	54	49	54	67	146	256	301	397	310	138	87
68 (T2)	114	90	79	96	160	317	544	647	613	503	324	227
112 (T19)	125	98	90	108	177	328	568	619	574	459	217	155
Group 4												
96 (T7)	50	37	39	43	59	233	548	467	444	420	23	37

The difference between the uncorrected HM total (477,297 kWh) and corrected HM total (495,513 kWh) of thermal energy delivered to the domestic HM is 18,216 kWh or +3.68%. The very small change provides confidence that the dataset is a reliable representation of the thermal energy consumed by the domestic units.

Figure 7.7 presents the values for primary energy consumption (Ej), thermal energy generation (E_{gen}) and delivered thermal energy (E_{del}) for the case study building.

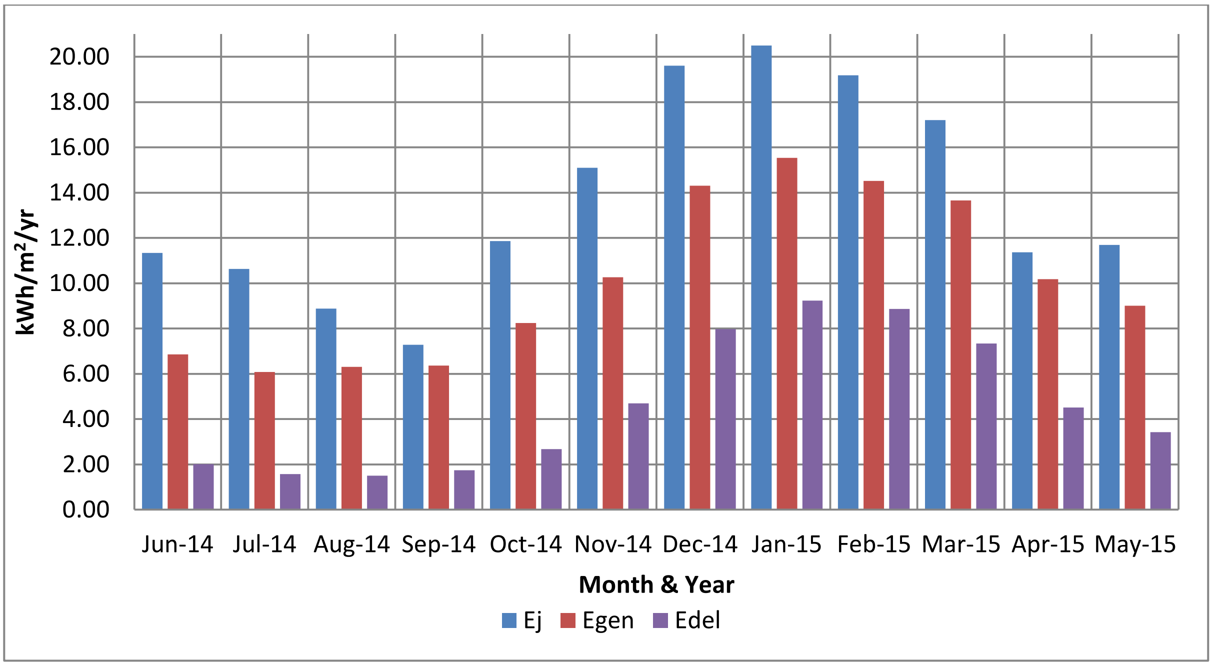


Figure 7.7: The Case Study Thermal Energy Values

7.4.3.4 Thermal and Electrical Energy Balance – CHP

Table 7.14 presents the CHP declaration of performance from the CHP manufacturer. The information identifies that the CHP did not consume or generate any energy for the month of September 2014, the reason for this is not known.

The CHP declaration is based on a number of assumptions that need to be corrected to be representative for the CS reference year, corrections include:

- Calorific Value
  - Declaration assumed: 10kWh/m^3
  - CS: 11.4-11.15 kWh/m^3
- Conventional Boiler Efficiency:
  - Declaration assumed: 80%
  - CS: 70-97% (see section 7.4.3.5)
- CO_2 emission factor for gas:
  - Declaration assumed: 0.184557 kgCO_2/kWh
  - CS: 0.194 kgCO_2/kWh

Table 7.14: CHP Declaration of Performance

CHP Declaration of Performance					
Month	Hours Run	Primary Energy (kWh/month)	Heat (kWh)	Electricity (kWh)	CO_2 Savings ($KgCO_2$)
June 2014	519	47570	28440	17030	9673
July 2014	534	48894	29232	17504	9942
August 2014	211	19349	11568	6927	3935
September 2014	0	0	0	0	0
October 2014	425	38880	23245	13919	5010
November 2014	519	47534	28418	17017	6126
December 2014	537	49101	29355	17578	6328
January 2015	513	46922	28053	16798	6047
February 2015	477	43570	26049	15598	56145
March 2015	282	25229	15083	9032	3251
April 2015	13	835	499	299	108
May 2015	223	19489	11652	6977	2512
Total	4,253	387,373	231,594	138,679	109,077

Correcting the primary energy consumption for the CV in the reference year calculates that the CHP used more primary energy than declared by the servicing company (table 7.15).

Table 7.15: Corrected CHP Primary Energy Consumption

CHP Primary Energy (Ej_{CHP})			
Month	Declared Primary Energy (kWh)	Corrected Primary Energy (kWh)	Difference (%)
June 2014	47,570	52,907	10.09%
July 2014	48,894	54,515	10.31%
August 2014	19,349	21,479	9.92%
September 2014	0.00	0.00	0.00%
October 2014	38,880	43,262	10.13%
November 2014	47,534	52,780	9.94%
December 2014	49,101	54,432	9.79%
January 2015	46,922	51,922	9.63%
February 2015	43,570	48,269	9.74%
March 2015	25,229	27,854	9.42%
April 2015	835	929	10.12%
May 2015	19,489	21,733	10.32%
Total	387,373	430,081	9.93%

Analysing the CHP primary energy consumption ($E_{j,CHP}$) and thermal energy generation ($E_{gen,CHP}$) identifies that the CHP accounted for 29% (0.29) of the total primary energy consumed (E_j) and 21% (0.21) of the total thermal energy generated (E_{gen}) (table 7.16).

Exceeding the predicted proportion of 8.5% of primary energy and 4% of thermal energy generated (section 7.4.2.4).

Table 7.16: CHP Fraction of Primary Energy and Thermal Energy Generated

CHP Fraction of Primary Energy and Generated Thermal Energy		
Month	Fraction of Primary Energy	Fraction of Thermal Energy
June 2014	0.52	0.46
July 2014	0.58	0.54
August 2014	0.27	0.21
September 2014	0.00	0.00
October 2014	0.41	0.32
November 2014	0.39	0.31
December 2014	0.31	0.23
January 2015	0.28	0.20
February 2015	0.28	0.20
March 2015	0.18	0.12
April 2015	0.01	0.01
May 2015	0.21	0.14
Total	0.29	0.21

7.4.3.5 Thermal Energy Balance – Gas Boilers

The three gas boilers do not contain any direct metering for primary fuel or heat generated. The energy consumed and generated must be calculated by the proportion of total primary fuel and total heat generated not provided by the CHP. This is represented as theoretical meters *G3* and *H2* on the metering diagram 7.1. Table 7.17 presents the calculated primary energy consumption ($E_{j,boilers}$) and thermal energy generation ($E_{gen,boilers}$), once the CHP has been deducted. Equation 8 can be applied to these figures to determine the gas boilers thermal efficiency. As the result, the thermal efficiency of the gas boilers has been determined as 81.93%, lower than predicted in the ES (94%) and SAP assessment (93%).

Table 7.17: Gas Boilers Energy Consumption, Generation and Thermal Efficiency

Gas Boiler Thermal Generation & Efficiency			
Month	Boiler Primary Energy Consumption (kWh)	Boiler Thermal Energy Generation (kWh)	Efficiency %
June 2014	48,253	32,760	67.89%
July 2014	40,268	25,068	62.25%
August 2014	57,692	44,732	77.54%
September 2014	64,977	56,800	87.42%
October 2014	62,600	50,355	80.44%
November 2014	81,852	63,182	77.19%
December 2014	120,478	98,245	81.55%
January 2015	130,925	110,547	84.44%
February 2015	122,862	103,451	84.20%
March 2015	125,573	106,717	84.98%
April 2015	100,469	90,301	89.88%
May 2015	82,565	68,748	83.26%
Total	1,038,515	850,906	81.93%

7.4.3.6 Distribution Heat Loss (E_{loss}) and Auxiliary Energy Consumption (E_{aux})

Distribution Heat Loss

The DHL (E_{loss}) is stated by the thermal energy leaving the heating plant (E_{gen}) and subtracting the sum of the energy delivered to the consumers (E_{del}) (table 7.18 and figure 7.8). The results demonstrate that the DHL for the reference year (54.23%) was significantly higher than that predicted by the SAP (9%).

Table 7.18: Heat Network Distribution Heat Loss

HN Distribution Heat Loss (E_{loss})					
Month	Total Thermal Generation (E_{gen})	Energy Delivered (E_{del})	Distribution Heat Loss (E_{loss})	Distribution Heat Loss (E_{loss})	Distribution Heat Loss
	kWh/month	kWh/month	kWh/month	kWh/m^2	%
June 2014	61,200	17,932	43,268	4.85	70.70%
July 2014	54,300	13,977	40,323	4.52	74.26%
August 2014	56,300	13,408	42,892	4.81	76.18%
September 2014	56,800	15,585	41,215	4.62	72.56%
October 2014	73,600	23,875	49,725	5.57	67.56%
November 2014	91,600	41,914	49,686	5.57	54.24%
December 2014	127,600	71,114	56,486	6.33	44.27%
January 2015	138,600	82,369	56,231	6.30	40.57%
February 2015	129,500	79,121	50,379	5.65	38.90%
March 2015	121,800	65,470	56,330	6.32	46.25%
April 2015	90,800	40,204	50,596	5.67	55.72%
May 2015	80,400	30,544	49,856	5.59	62.01%
Total	1,082,500	495,513	586,987	65.81	54.23%

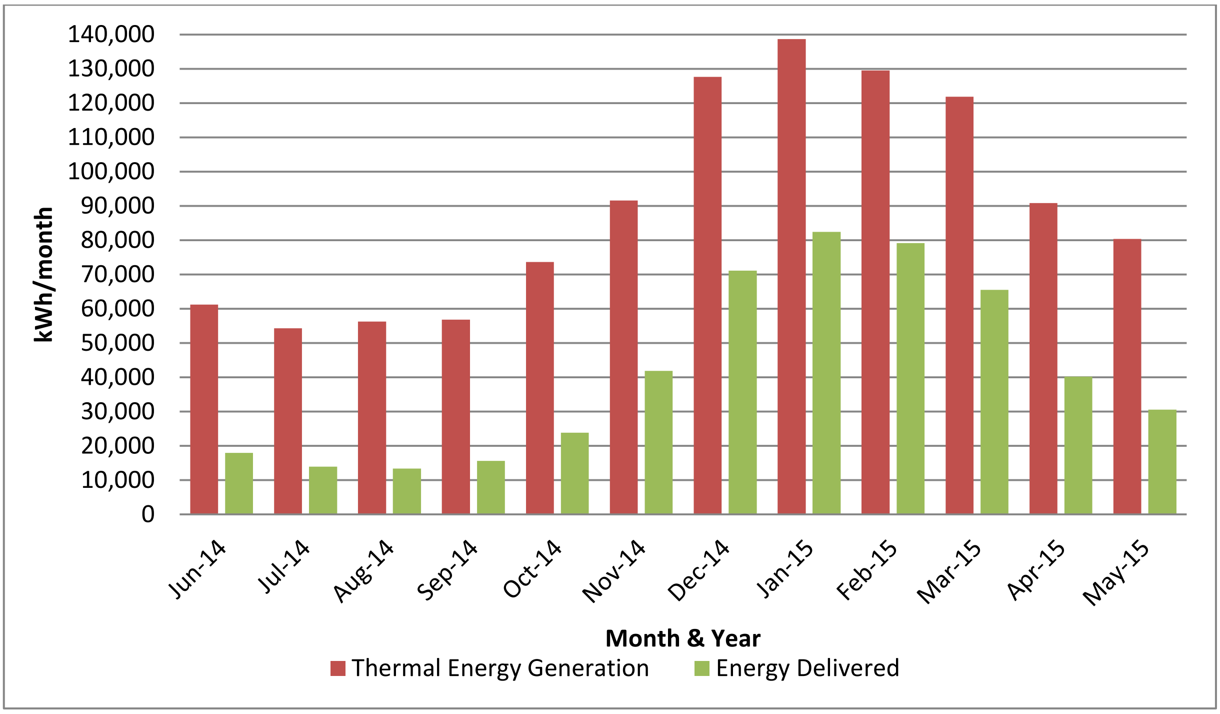


Figure 7.8: Heat Network Distribution Heat Loss

Auxiliary Energy Consumption

The energy centre is sub-metered for AE (meter reference *E5,* figure 7.1). However, the meter does not have a remote reading facility. Meter reading were taken visually over several months to provide an estimate of the daily electrical consumption (table 7.19). It is recognised that monthly meter readings would have provided an accurate account of consumed AE. However, the average daily consumption was observed to be relatively constant and within a range of less than 1.5kWh/day. Therefore, it is considered to be a reasonable estimation of the total consumed AE.

Table 7.19: Auxiliary Energy Consumption Meter Readings

Meter Reading Date	Reading kWh	Consumption kWh	Days Between Readings	Average Consumption kWh/day
10.07.14	318,185.5	-	0	-
05.11.14	339,692.5	21,507.0	119	180.73
07.12.14	345,501.0	58,08.5.0	32	181.52
22.12.14	348,232.0	2,731.0	15	182.07

Table 7.20: Auxiliary Energy Consumption and Faction of Delivered Heat

Auxiliary Energy (E_{aux})				
Month	Electrical Consumption kWh/month	Electrical Consumption kWh/m^2	Factor of Delivered Heat to Sub-Stations (E_{del})	Factor of Thermal Energy Generated (E_{gen})
June 2014	5,443	0.61	0.30	0.09
July 2014	5,625	0.63	0.40	0.10
August 2014	5,625	0.63	0.42	0.10
September 2014	5,443	0.61	0.35	0.10
October 2014	5,625	0.63	0.24	0.08
November 2014	5,443	0.61	0.13	0.06
December 2014	5,625	0.63	0.08	0.04
January 2015	5,625	0.63	0.07	0.04
February 2015	5,080	0.57	0.06	0.04
March 2015	5,625	0.63	0.09	0.05
April 2015	5,443	0.61	0.14	0.06
May 2015	5,625	0.63	0.18	0.07
Total	66,225	7.42	0.13	0.06

Table 7.20 calculates the proportion of AE consumption to delivered thermal energy (13%) and generated thermal energy (6%). Section 7.4.2.6 identified that the SAP allowed zero energy consumption for AE. To provide a predicted comparison the calculation method from SAP 2012 was adopted (1% of the heat delivered). Therefore, the results from the CS demonstrate that the AE consumption (13%) is significantly higher than the predicted (1%). Section 7.4.3.3 has shown that there is a significant difference between generated thermal energy (E_{gen}) and delivered thermal energy (E_{del}). Therefore, it may be more appropriate to predict AE based on a proportion of generated energy rather than delivered.

7.4.3.7 Summary of Energy Figures

Through investigation of the energy consumption and generation of the HN-CHP system, the relevant energy performance figures have been identified (table 7.21).

Table 7.21: Case Study Summary of Energy Figures

Summary of Energy Figures			
EPI	-	kWh	kWh/m^2
Primary Energy Consumption	E_j	1,468,596	164.64
Generated Thermal Energy	E_{gen}	1,082,500	121.36
Delivered Thermal Energy	E_{del}	495,513	55.55
CHP Electrical Generation	E_{CHP}	138,679	15.15
Auxiliary Energy	E_{aux}	66,225	7.42
Distribution Heat Loss	E_{loss}	568,987	65.81

7.4.4 Results of the Post-Occupancy Evaluation

This section compares the predicted energy and CO_2 with that observed in the case study for the reference year.

7.4.4.1 The Energy Strategy - Heat Network

Two performance criteria were defined to evaluate the justification of HN technology.

1) What is the thermal generation efficiency of the energy centre gas boilers? The assumed thermal efficiency is 94%.

The thermal generation efficiency of the gas boilers was calculated for each month and the results ranged between 62.25% and 89.88%. The overall efficiency for the reference year was 81.93%. The gas boiler efficiency increased in relation to fraction of heat load (figure 7.9).

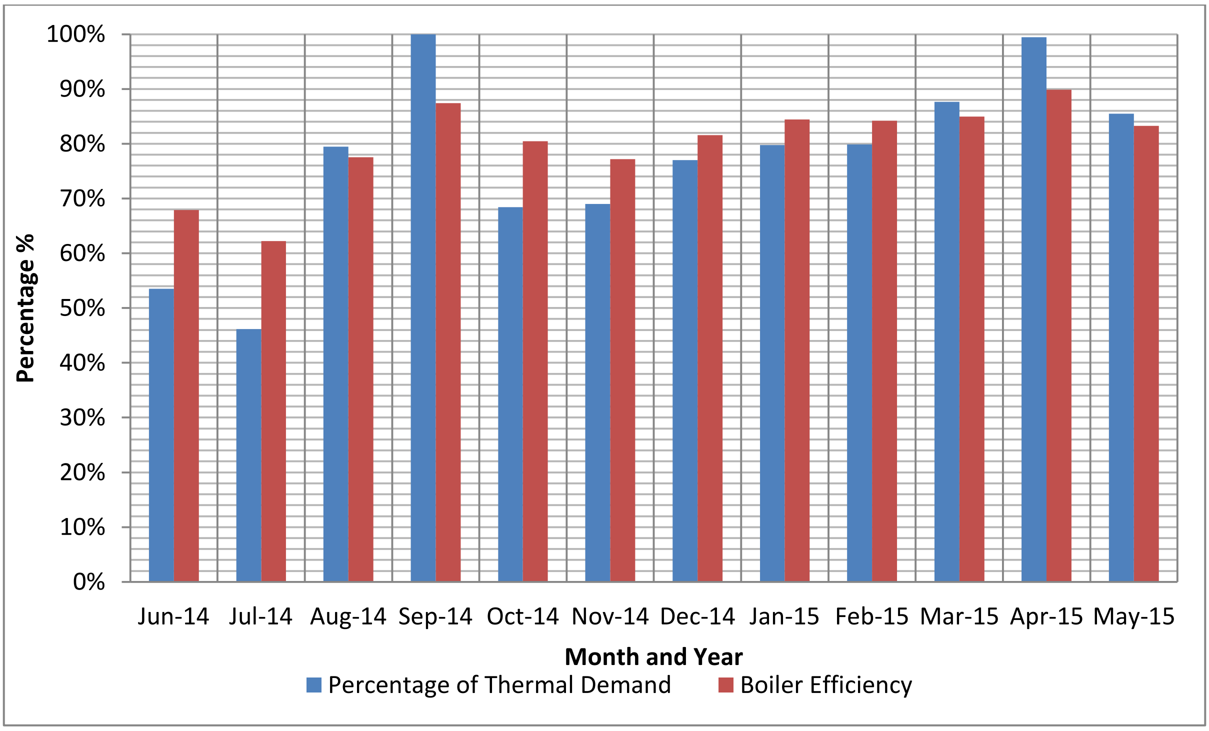


Figure 7.9: Relationship of Thermal Demand to Gas Boiler Efficiency

The ES applied the HN and boiler thermal efficiency prior to the adoption of a CHP. Therefore, a fair comparison of efficiency would be when the gas boilers fraction is 1.0. The gas boilers provided the highest thermal load during September 2014 (1.0) and in April 2015 (0.99). The boiler thermal efficiencies for these two months were 87.42% and 89.88% respectively. Therefore, the assumed thermal generation efficiency, defined as performance criteria 1, was not achieved even in the best performing month.

In relation to the primary energy requirement (E_j) per m^2 floor area, the poorer thermal efficiency resulted in an additional 5.9 kWh/m^2 and 1.148 $kgCO_2/m^2$.

2) Does the HN system provide a CO_2 saving of 52,515 $kgCO_2/yr$ over theoretical domestic gas boiler systems?

The CO_2 of a HN without a CHP is defined by equation 10 (p.177). As the CHP has been removed from this comparison, the gas boilers efficiency is taken as 89.88%. Heat losses due to distribution must be included in the energy balance (CIBSE, 2015). The ES does not state if CO_2 figures include network DHL (E_{loss}). Therefore, the HN CO_2 is based on the total generated energy (E_{gen}), rather than delivered (E_{del}). Furthermore, AE (E_{aux}) to deliver the heat to the consumers must be included. There is no DHL (E_{loss}) and AE (E_{aux}) associated to the domestic gas boilers.

Table 7.22: Heat Network CO_2 Emissions (without CHP)

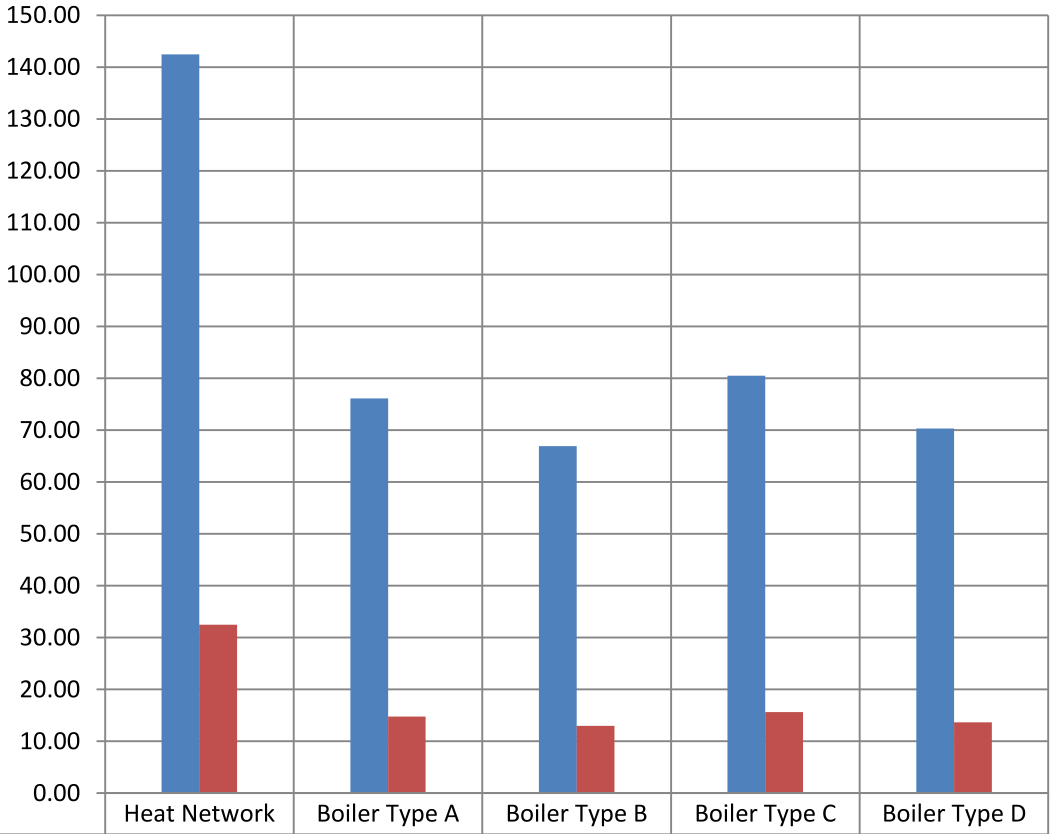
Heat Network CO_2 Emissions (without CHP)							
Month	E_{gen}	η_{boiler}	$E_{f,boiler}$	E_{aux}	$E_{f,elec}$	CO_2 Emissions	CO_2 Emissions
	kWh	%	-	kWh	-	$KgCO_2$	$KgCO_2/m^2$
June 2014	61,200	0.8988	0.194	5,443	0.422	15,507	1.74
July 2014	54,300	0.8988	0.194	5,625	0.422	14,094	1.58
August 2014	56,300	0.8988	0.194	5,625	0.422	14,526	1.63
September 2014	56,800	0.8988	0.194	5,443	0.422	14,557	1.63
October 2014	73,600	0.8988	0.194	5,625	0.422	18,260	2.05
November 2014	91,600	0.8988	0.194	5,443	0.422	22,068	2.47
December 2014	127,600	0.8988	0.194	5,625	0.422	29,915	3.35
January 2015	138,600	0.8988	0.194	5,625	0.422	32,289	3.62
February 2015	129,500	0.8988	0.194	5,080	0.422	30,096	3.37
March 2015	121,800	0.8988	0.194	5,625	0.422	28,663	3.21
April 2015	90,800	0.8988	0.194	5,443	0.422	21,896	2.45
May 2015	80,400	0.8988	0.194	5,625	0.422	19,727	2.21
Total	1,082,500	0.8988	0.194	66,225	0.422	261,597	29.33

The BS EN 15316-4-5:2007 states that when the HIU is located within the heated space, no thermal 'standing' losses should be taken. As the domestic gas boilers would also be located within the heated space, no standing losses are taken. The total heat delivered to the HIU (E_{del}) has been defined as the 'useful' thermal load required by the dwellings, therefore E_{del} will be the thermal load to be provided by the individual domestic gas boilers. The comparison for the CO_2 savings will be the delivered energy to the consumers (E_{del}) generated by a domestic gas combination boiler[13] with seasonal efficiencies ranging from 73%-83% (0.73-0.83) (SAP, 2005 table 4b). In situ monitoring of domestic boilers efficiencies has found a mean efficiency of 82.5% (EST, 2009), this is comparable with boiler type B.

- Boiler Type A Efficiency – 75%
- Boiler Type B Efficiency – 83%
- Boiler Type C Efficiency – 69%
- Boiler Type D Efficiency – 79%

Figure 7.10 demonstrates that the HN system has consumed more energy and emitted more CO_2 than any comparable domestic combination gas boiler.

[13] Combination Boiler – central space heating and instantaneous generation of HWS



	Heat Network	Boiler Type A	Boiler Type B	Boiler Type C	Boiler Type D
kWh/m2	142.44	76.10	66.93	80.51	70.32
KgCO2/m2	32.46	14.76	12.98	15.62	13.64

Figure 7.10: Primary Energy and CO_2 Emissions of a Heat Network and Individual Boilers

The results demonstrate that performance criterion 2 has not been achieved. The HN emitted twice as much CO_2 than the least efficient comparable individual boiler (type C). In relation to the total thermal energy requirement for the dwellings (E_{del}). The HN system has emitted 16.84 $kgCO_2/m^2/yr$ more CO_2 than the least thermally efficient theoretical domestic gas boiler (type C) and 19.48 $kgCO_2/m^2/yr$ more than the most efficient (type B).

Summary of Results

The results have shown that the predictions made in the ES were not achieved in practice. The gas boilers failed to achieve the thermal efficiency expected, although, the efficiency was found to be higher than any of the theoretical individual boilers, which was one of the prominent motives for adopting a HN (see chapter 6). The analysis has demonstrated that the adoption of the HN has resulted in a doubling of CO_2 compared to individual domestic gas boilers, the reverse of the ES intention.

7.4.4.2 The Energy Strategy - CHP

This section evaluates the two performance criteria set out in section 7.3.4, which relate to the justification for the adoption of a CHP:

> **1) Does the CHP reduce the CO_2 compared to a HN without CHP? and what is the potential saving in percentage reduction? The predicted reduction is 9%.**
>
> **2) What is the value of $kgCO_2$ savings attributable to the CHP? The predicted saving is 28.3 tonnes of CO_2.**

The CO_2 emissions of the HN without a CHP (equation 10) and with a CHP (equation 11) have been calculated (table 7.22 in section 7.4.4.1 and 7.23 below). The contribution from the CHP was removed for equation 10 and therefore, the gas boilers efficiency was taken as 89.88%. For equation 11 the gas boilers efficiency will remain as the observed from the meter data (figure 7.9).

Table 7.23: Heat Network with CHP CO_2 Emissions

Heat Network CO_2 Emissions with CHP									
Month	E_{gen}	η_{boiler}	E_j	E_{aux}	$E_{gen,CHP}$	$E_{j,CHP}$	$E_{f,CHP}$	E_{CHP}	CO_2 Emissions
	kWh	-	kWh	kWh	kWh	kWh	-	kWh	$KgCO_2$
Jun-14	61,200	0.6789	90,143	5,443	28,440	52,907	0.194	17,030	12,249
Jul-14	54,300	0.6225	87,225	5,625	29,232	54,515	0.194	17,504	10,819
Aug-14	56,300	0.7754	72,612	5,625	11,568	21,479	0.194	6,927	13,798
Sep-14	56,800	0.8742	64,977	5,443	0	0	0.194	0	14,903
Oct-14	73,600	0.8044	91,498	5,625	23,245	43,262	0.194	13,919	15,005
Nov-14	91,600	0.7719	118,667	5,443	28,418	52,780	0.194	17,017	18,750
Dec-14	127,600	0.8155	156,476	5,625	29,355	54,432	0.194	17,578	26,322
Jan-15	138,600	0.8444	164,149	5,625	28,053	51,922	0.194	16,798	28,305
Feb-15	129,500	0.8420	153,798	5,080	26,049	48,269	0.194	15,598	26,484
Mar-15	121,800	0.8498	143,322	5,625	15,083	27,854	0.194	9,032	27,008
Apr-15	90,800	0.8988	101,024	5,443	499	929	0.194	299	21,798
May-15	80,400	0.8326	96,559	5,625	11,652	21,733	0.194	6,977	18,644
Total	1,082,500	0.8193	1,321,171	66,225	231,594	430,081	0.194	138,679	234,085

The ES predicted that the inclusion of a CHP would save 28,334 $kgCO_2$/yr, equal to 9%, compared to a HN without a CHP. The results have identified that actual saving was 27,512 $kgCO_2$/yr equivalent to 10.52%. Although, the CO_2 saved was 822$kgCO_2$ less than predicted, the overall percentage saved was exceeded by 1.52%. Furthermore, it was found that in September 2014 and April 2015, the CHP provided none or minimal energy. If the CHP had been operational for a greater number of hours during these two months, the CO_2 savings would have been exceeded.

The CHP *Declaration of Performance* certificates state that the CHP ran for 4,253 of the expected 6,297 hours in the reference year. A reduction in running hours was predicted in the ES:

"The development does not lend itself to this form of technology because there is not a good mixed energy usage, allowing the continual running of the engine...we will also be exploring the possibility of connection of our scheme with others in the local area, which would allow the engine to run more hours per day."

Summary of Results

The results have shown that the predictions made in the ES were reasonably achieved in practice. The CHP provided a CO_2 saving compared to a HN only system.

7.4.4.3 The Standard Assessment Procedure

In this section the SAP figures are compared with the corresponding figures from the CS data. The SAP worksheets provided the source of figures relating to: primary energy consumed (Ej), AE (E_{aux}), delivered thermal energy (E_{del}), CHP electrical generation (E_{CHP}), DHL (E_{loss}).

Primary Energy Consumption (E_j)

Primary energy for this case study refers to the energy consumed by each technology; primary energy is measured at the sites utility meter (figure 7.1 meter reference G1). The results have shown a significant difference between the predicted (SAP and SAP*) and observed primary energy consumption. It has been found that twice as much primary energy was used than the SAP* predicted (figure 7.11). The three gas boilers provided a thermal fraction of 0.79 (79%) of the total annual thermal energy generated (E_{gen}). Referring to the SAP worksheets (box 84*) the predicted thermal factor was designed to be 0.96. Therefore, the CHP provided a greater proportion of thermal generation than predicted. The reduced thermal efficiency of the CHP would result in higher primary energy consumption (E_j). It has also been identified that the actual thermal efficiencies were 81.89% for the gas boilers and 53.85% (thermal) for the CHP. Referring to the SAP worksheets (box 109* and 102*) the thermal efficiencies were predicted to be 93% and 47% respectively. Correcting the SAP* data further to allow for the increased thermal fraction (SAP**) and thermal efficiencies (SAP***), the performance gap is reduced (figure 7.11). However, the gap is still significant. The analysis has shown that the primary thermal energy consumption of the HN-CHP system has significantly exceeded the predicted consumption.

Figure 7.11: Comparison of Corrected SAP Data for Primary Energy Consumption

Thermal Energy Generation (E_{gen})

Figure 7.12 shows that the actual thermal energy generation (E_{gen}) was around a third higher than predicted. The difference increased when the data is corrected for degree-days (SAP*). There is no change for thermal fraction (SAP**) or thermal efficiency (SAP***), however, these are shown for consistency. The results have demonstrated that the thermal energy generated from the HN-CHP system has significantly exceeded the predicted values.

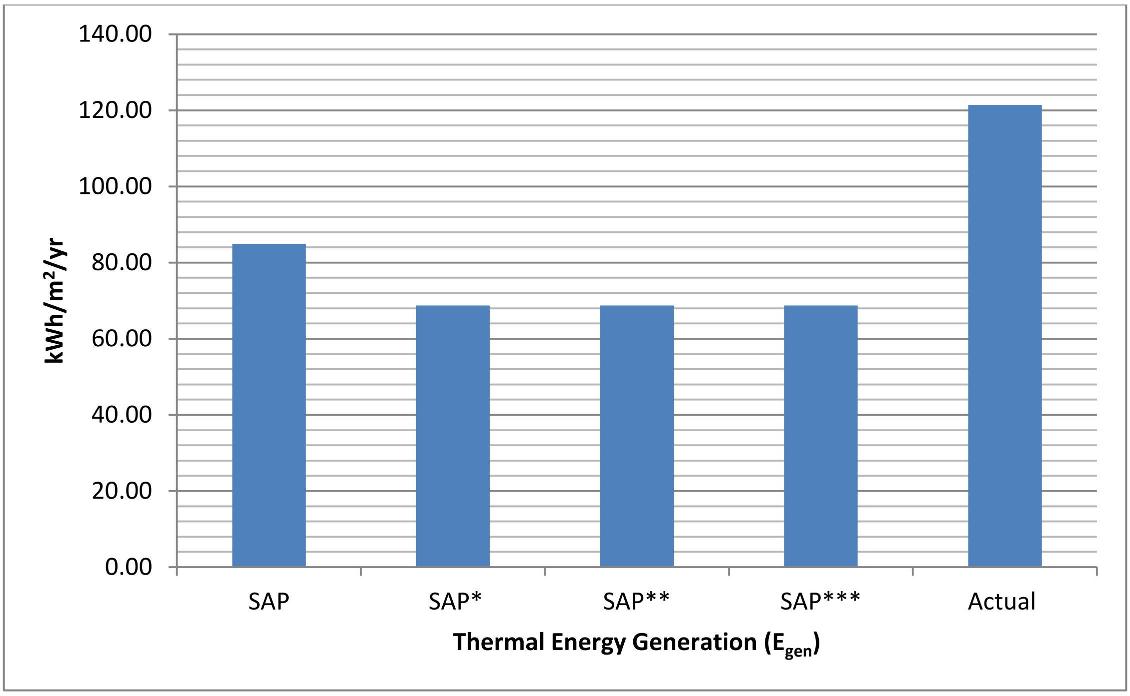


Figure 7.12: Comparison of Thermal Energy Generation

Thermal Energy Delivered (E_{del})

The thermal energy delivered (E_{del}) is the useful energy requirement of the residents to meet the domestic SH and DHW demands (figure 7.13). It is noted that for the evaluation of the thermal energy delivered there is no difference when applying thermal fractions (SAP**) and thermal efficiencies (SAP***) as these do not affect the 'useful' energy requirement. However, these they have been shown for consistency.

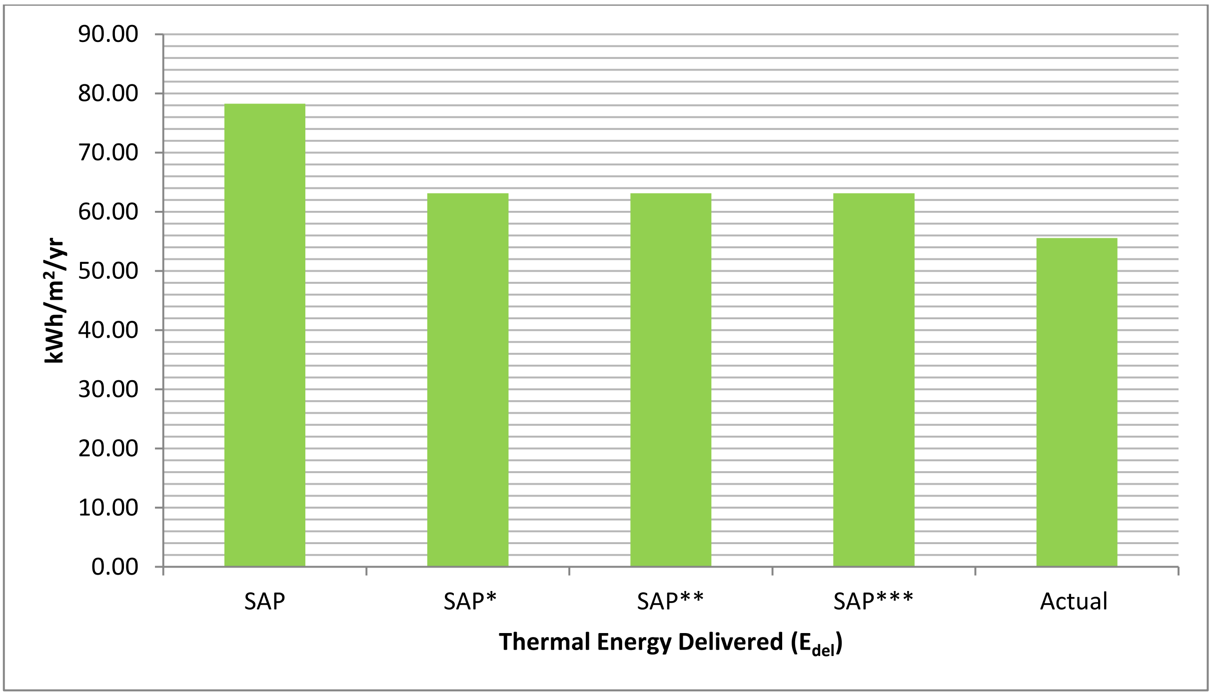


Figure 7.13: Comparison of Thermal Energy Delivered

Figure 7.13 demonstrates that the thermal energy delivered to the dwellings was almost a third lower than predicted by the SAP assessment. However, this is reduced when the figures are corrected (SAP*). The findings have demonstrated that the energy demand for heating is lower than predicted, demonstrating an improvement in the energy efficient measures of the building. Furthermore, the results suggest that the SAP assessment can provide a reasonable assessment of domestic heat demand, if matched to external conditions (SAP*). Although, it is acknowledged that there are a variety of contributing factors to domestic energy demand, for example occupant's behavior (see Delzendeh et al, 2017). In accordance with the boundaries of this research (section 5.3.4) the thermal warming of the building mass resulting from HN's distribution heat loss has not been analysed.

Heat Network Distribution Heat Losses (E_{loss})

The SAP methodology applies a DLF to the thermal energy demand (E_{del}) to calculate DHL. The average DLF from the SAP worksheets was found to be 1.09 (9%). To calculate the actual DHL, the energy delivered to the consumer HM (E_{del}) is subtracted from the thermal energy leaving the energy centre (E_{gen}). Figure 7.14 compares the DHL (E_{loss}).

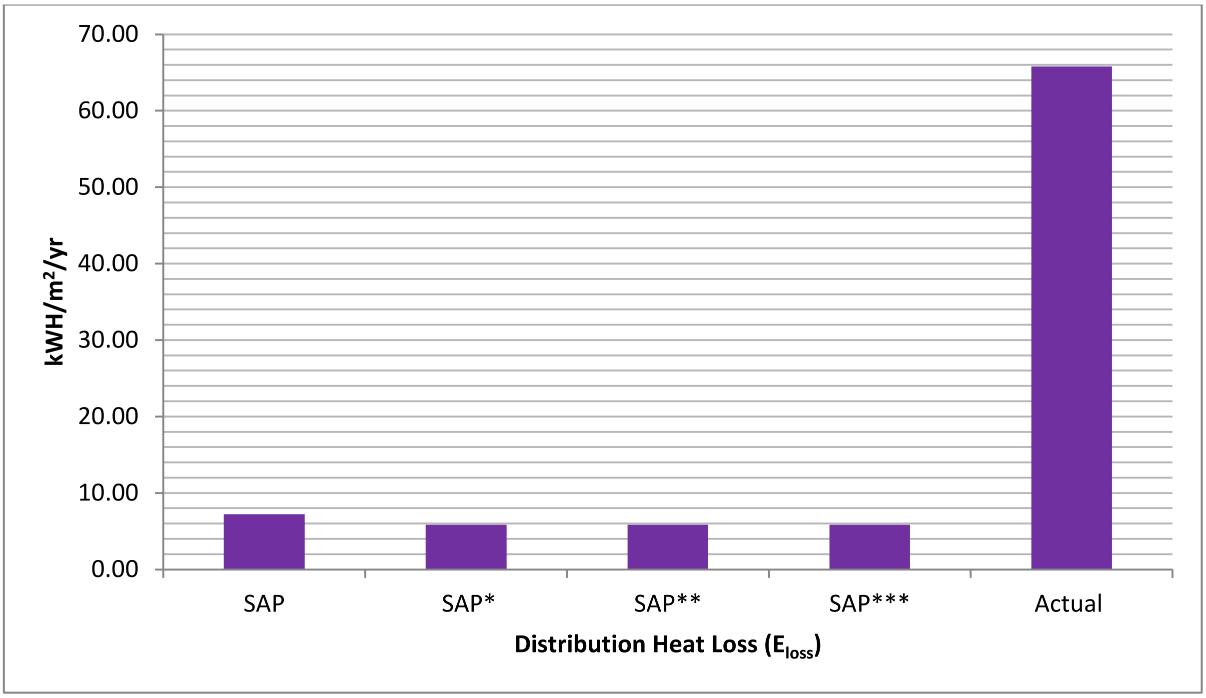


Figure 7.14: Comparison of Distribution Heat Loss

Figure 7.14 has shown that the SAP assessment significantly underestimated the DHL associated to the HN. The difference being a factor of 9. The difference increases with SAP* owing to the decreased prediction of useful thermal energy (E_{del}). This analysis suggests that DHL is a key area for HN evaluation.

Auxiliary Energy Consumption (E_{aux})

The AE consumption is zero (0 kWh/m^2) for the SAP 2005 and therefore no comparison can be made. For the corrected values (SAP*, SAP**, SAP***) the methodology under SAP 2012 was applied (1% of E_{del}). The meter readings have estimated AE consumption of 7.42kWh/m^2. Figure 7.15 compares the AE (E_{aux}) consumption.

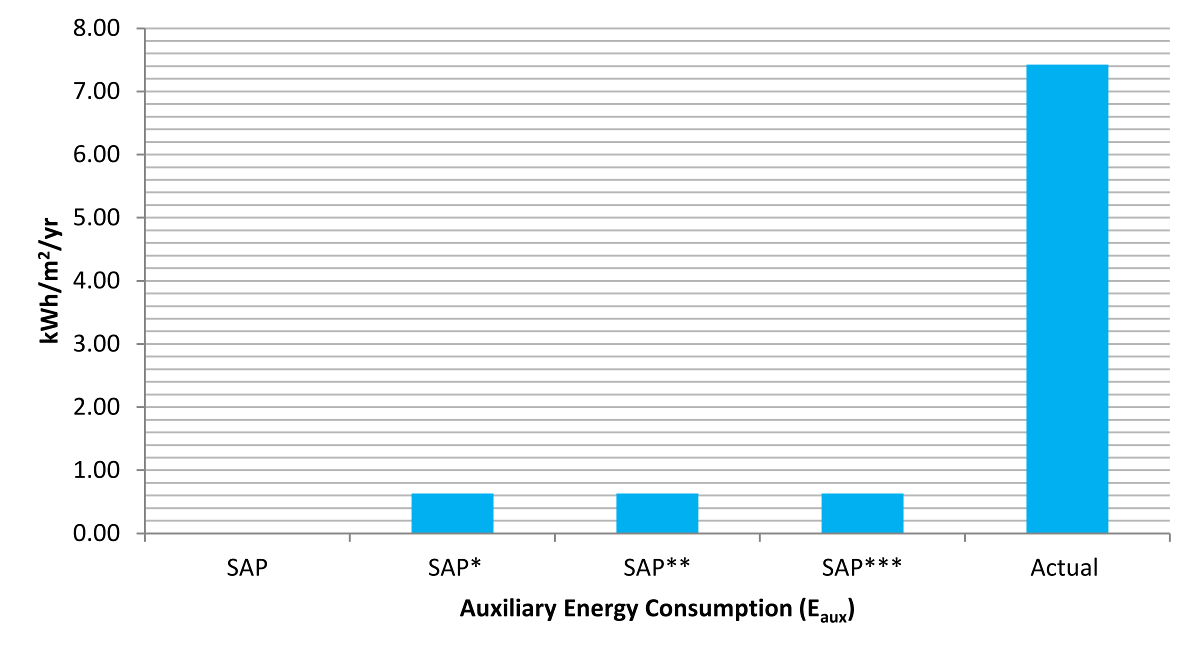


Figure 7.15: Comparison of Auxiliary Energy Consumption

The zero energy demand attributed to AE in the predicted SAP (2005) is an instant identification of an energy performance gap when considering this element of the HN-CHP system. However, the results have also shown that the current SAP (2012) methodology significantly underestimated the AE associated to the HN, in this instance by a factor of 12. This analysis suggests that AE is also a key area for HN evaluation.

7.4.4.4 Energy Performance Indicators

This section calculates and evaluates the findings for each of the EPI, to determine if an energy performance gap can be associated to the HN-CHP system. Secondly, the EPI are evaluated to determine if a more realistic expectation of performance in practice could have been expected at an early design stage.

Heat Density (kWh/m²)

The analysis of ES documents (chapter 6) identified that HD was often cited as a justification for adopting a HN-CHP. However, the references to HD were found to be notional concepts of 'density' rather than technical evaluation. Chapter 3 analysed the industry and academic literature related to minimum threshold of HD. The GLA suggested that 50kWh/m^2/year as the minimum threshold (GLA, 2011c), while the EU suggest a much higher figure of 130kWh/m^2/year (EC, 2018a).

HD is typically associated with site area, as buildings being connected to a HN are distributed across large urban or rural areas (GLA, 2011c). However, in the case of multi-story apartment buildings the heat demand areas are stacked one above the other on multiple floor levels. The CS site area is 7,600m^2 (0.76 hectares), whereas the buildings total heated floor area is 8,920m^2 (equivalent of 0.89 hectares). HD has been investigated in relation to the total site area and also the total heated floor area (figure 7.16) to examine the effect on HD and the potential outcome of feasibility stage assessment.

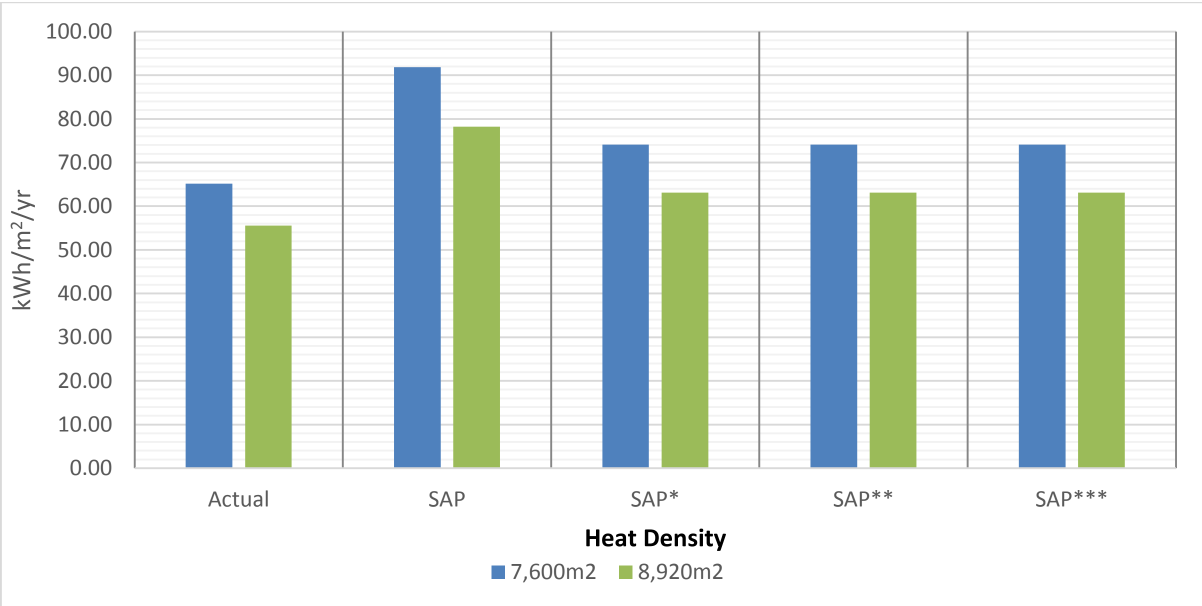


Figure 7.16: Comparison of Heat Density

Figure 7.16 demonstrates that the actual building HD was around a third lower than predicted by SAP. However, this is expected given that DH is a function of heat demand and lower heating demand was observed (section 7.4.3.3). When the SAP was corrected (SAP*, SAP** & SAP***), the difference is considerably smaller and reasonable close to the actual. This would suggest that the SAP can provide a reasonable estimate of a sites HD for early stage feasibility assessment. However, the difference between the SAP and SAP*, demonstrates the significant influence that local ambient temperatures can have on HD. This suggests that feasibility assessments should considered a range of weather conditions to understand how HD could be affected through the operational life of the building, including changes due to climate change.

The total heated floor area of the building is larger than the site area, therefore HD was reduced when taken as a proportion. The higher demand for housing in London is resulting in greater numbers of taller and higher density buildings. The ratio of site area to heated floor area will correspondingly increase. Therefore, for multi-occupied residential buildings with HNs, heated floor area would be a better indication of HD.

The HD has been shown to be higher than the GLA minimum threshold. Therefore, in terms of GLA policy, the CS would be considered suitable for a HN. However, the HD is much lower than the EU threshold. These results identify an area of possible future research, to examine the HD of newly built apartment buildings (those with and without HN) and how this relates to performance in practice. This type of research would aid the evaluation of minimum HD threshold for HNs.

To further evaluate the importance of HD the three heat distribution circuits of the HN were individually analysed. The three distribution circuits vary in length (m) and the number of consumers. The circuits were analysed to compare: the heat supplied to the circuit, heat delivered to consumers, DHL, and HD. The CS design drawings identified three circuits as 'riser 1', 'riser 3' and 'riser 4'. From the drawings the pipework sizes (ømm) and pipework length (m) for each riser were measured.

The HM on each circuit are referenced as *H4, H5 and H6* in the metering diagram (figure 7.1). Comparing the total sum of the three circuits HMs with the total heat generation (E_{gen}) (*H3*), identifies that there is a relatively small difference in total energy. This is attributed to the heat loss from pipework, equipment and fittings within the energy centre. The results of the circuit analysis are presented in table 7.24 and figure 7.17.

Table 7.24: Comparison of Riser Distribution Heat Loss and Heat Density

Heat Density & Distribution Heat Loss per Riser						
	Number of Consumers	Total Length of Pipework	Energy Consumed ($E_{gen,riser}$)	Energy Delivered ($E_{del,riser}$)	Distribution Heat Loss ($E_{loss,riser}$)	Riser Heat Density
	-	m	kWh/year	kWh/year	%	kWh/m^2
Riser 1	13	133	120,230	39,303	67.31%	36.00
Riser 3	100	678	653,200	359,447	44.97%	61.17
Riser 4	25	227	232,290	96,763	58.34%	49.59

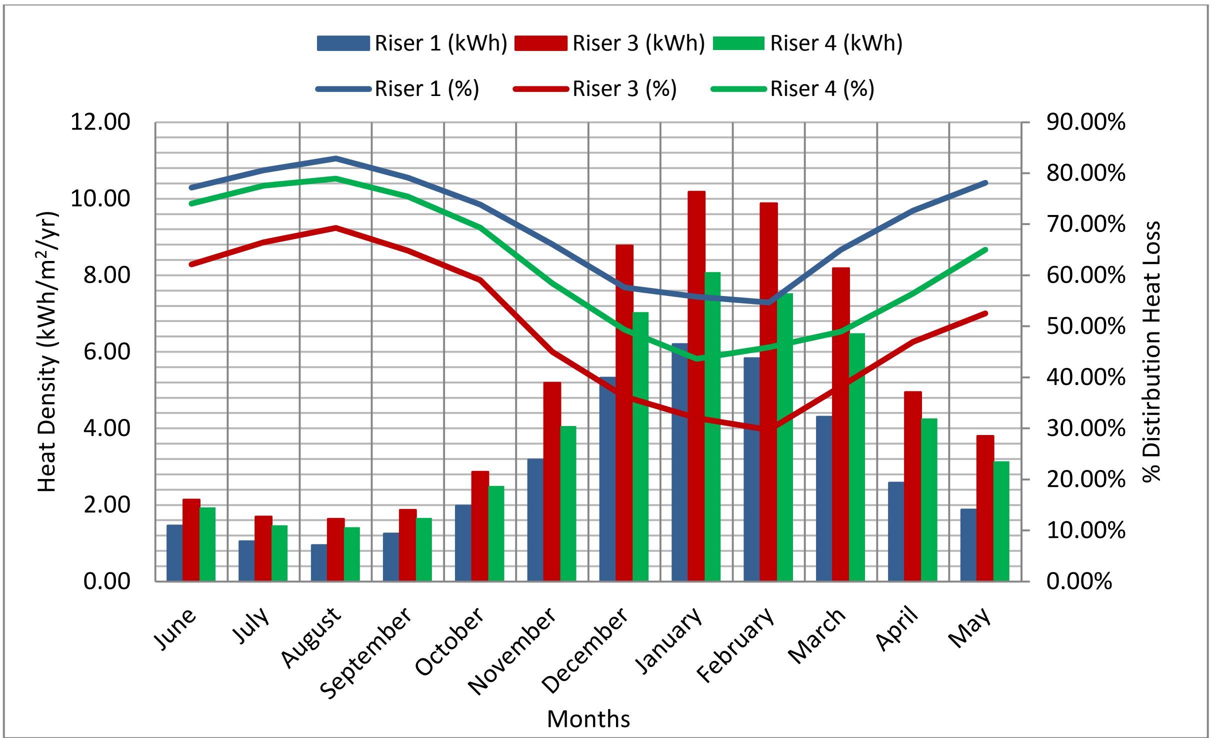


Figure 7.17: Comparison of Riser Heat Density and Distribution Heat Loss per Month

The results from the analysis indicate several important factors. Firstly, riser 3 has the highest HD, and the lowest proportion of DHL. This is despite having the longest distribution pipework (m) and therefore highest losses. This corroborates that scale of DHL could be related to HD – the higher the HD the lower the percentage DHL (see chapter 3). However, the results have also demonstrated that riser 3 has the lowest proportion of pipework length per heat consumer (6.73m/consumer), compared to riser 1 (10.2m/consumer) and riser 4 (9.08m/consumer). This could also account for the lower proportional DHL in riser 3. Riser 1 has the highest pipework length per consumer, lowest HD and correspondingly the highest DHL. These findings suggest that HD on its own is not an adequate measure to predict the performance of a HN. Pipework length in relation to HD (i.e. LHD) has been found to be a more relevant factor.

Linear Heat Density (kWh/m)

The LHD expresses heat demand per length of network distribution (kWh/m). The total length of the HN distribution pipework has been measured from the CS design drawings. From the energy centre boundary to each HIU the total length has been measured as 1,038m. Table 7.25 demonstrates the actual and predicted LHD. The SAP** and SAP*** have not been included as the delivered energy (E_{del}) remains constant with SAP*.

Table 7.25: Comparison of Linear Heat Density.

Linear Heat Density (LHD)			
	Pipework Length	Energy Delivered by HN	LHD
	m	kWh/yr	kWh/m
Actual	1,038	495,513	477
SAP	1,038	697,896	672
SAP*	1,038	563,083	542

*Corrected for degree-days

The actual LHD is considerably lower compared to the range of LHD presented in the earlier examined industry and academic research (see section 3.6.1). The earlier investigation of LHD (chapter 3) identified graphical curves that are available that demonstrate the relationship between LHD and DHL. Figures 7.18 and 7.19 plot the established LHDs to illustrate how the predicted level of DHL could have been estimated from LHD. The actual LHD is also plotted to demonstrate the difference in the CS performance compared with other European HNs.

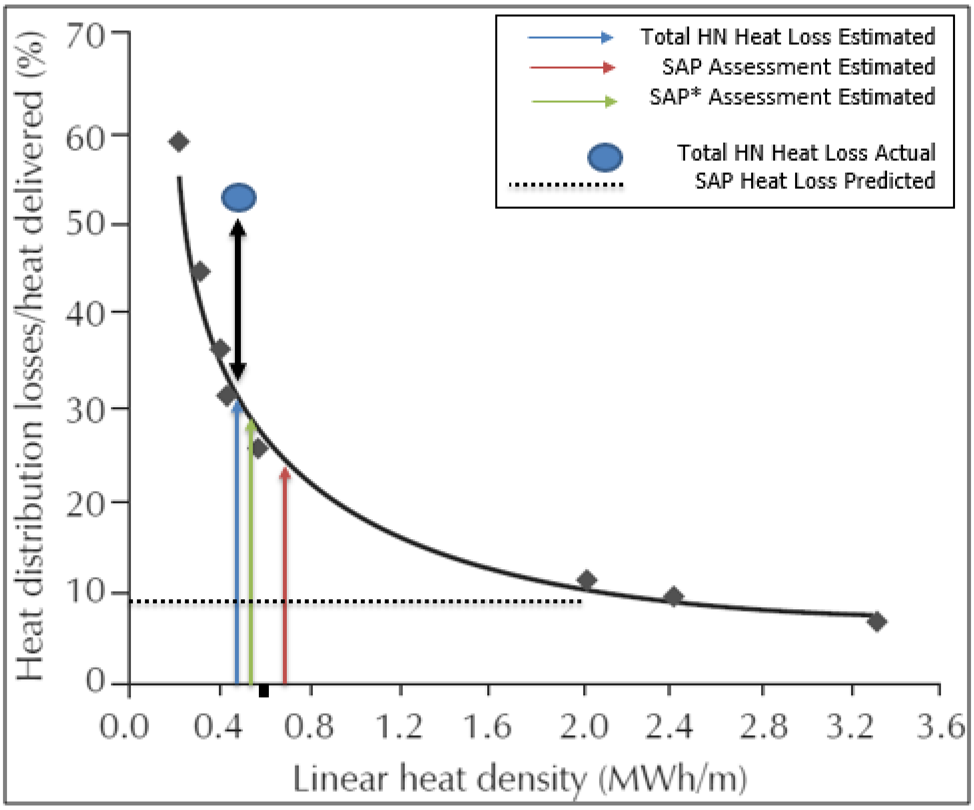


Figure 7.18: Linear Heat Density to Distribution Heat Loss (adapted from BRE, 2016)

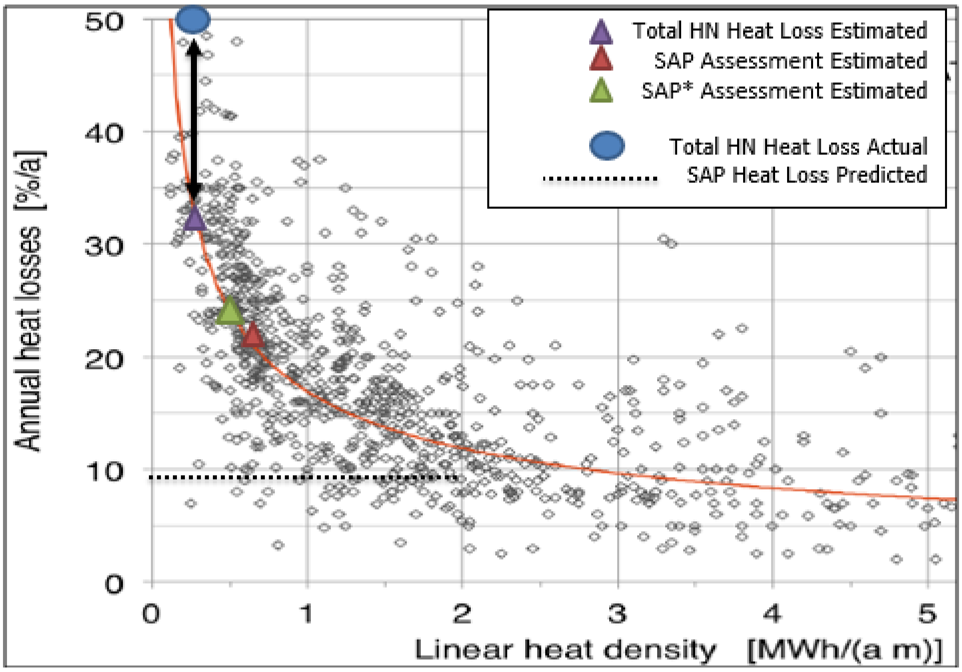


Figure 7.19: Linear Heat Density to Distribution Heat Loss Comparison with European Heat Networks (adapted from Nussbaumer et al, 2014)

Figure 7.18 and 7.19 demonstrate that the corresponding DHL to the SAP LHD (21%) and SAP* LHD (24%) significantly exceeds that predicted in the SAP methodology (9%). Therefore, evaluating the SAP LHD during feasibility stage could have indicated that the DHL was likely to be higher in practice, based on industry data and surveys of operational HNs.

Figure 7.19 demonstrates that only one HN has a DHL lower than 9% with a similar LHD to the CS system.

The findings also demonstrate that the DHL observed in the CS (54%) exceeds what could have been expected when comparing to the DHL curve (32%). The additional difference (22%) is likely the result of site specific conditions (weather conditions; system temperatures; issues associated to design, installation, commissioning, etc.).

The analysis of LHD has informed this research that the SAP methodology for estimating DHL is unlikely to determine the HN losses with any reasonable accuracy. Furthermore, unique site conditions will likely influence the DHL.

Distribution Loss Factor (DLF)

To calculate the DLF the following HN characteristics need to be known (equation 3):

- Total Delivered Heat (E_{del})
- Total Length of pipework (m)
- Linear Heat Loss per metre of pipework (W/m)

A HN will inevitably consists of pipework with various diameters, as pipe diameter is related to the required flow rate and pressure demand of that point in the system. DLF can be calculated from the linear heat loss relative to the pipe diameter. Linear heat loss is directly related to pipe diameter owing to the change in surface area. BRE's (2016) consultation document calculated DLF based on individual pipe diameters and lengths. Therefore, for the purposes of this CS the losses will be calculated for pipe diameters and lengths as the design drawings provide this information (table 7.26). HN distribution routes are expected to be calculated within a feasibility assessment (GLA, 2013a; CIBSE, 2015).

The linear heat loss (W/m) is calculated based on insulation thickness and thermal conductivity. Consistent with the BRE study, the calculated heat loss does not account for additional losses owing to uninsulated fittings (e.g. flanges), substandard installation or operational damage (BRE, 2016). The design drawings illustrate the insulation design intent, including thickness (mm) (appendix 3). Photos demonstrate that the standard of installation was recognisable with the design intent (appendix 4). However, the full extent of the distribution was not available for visual inspection and therefore the quality of insulation cannot be categorically determined. It is believed, given the scale of observed DHL (section 7.4.3.6), that there are likely to be sections of pipework with inferior installation or missing insulation.

Linear heat loss calculations were undertaken (table 7.26) using industry available design simulation software 'Bentley Hevacomp version V8i' (Bentley Systems, 2015). The BRE (2016) study and CS information (design drawings, schedules, inspections, and photos) provided the following information:

- Insulation Heat Loss Coefficient (Lambda Value) – 0.024 W/mk (appendix 3)
- Insulation thickness – drawing details (appendix 3)
- Design Flow Temperature – 80^{o}C (appendix 3)
- Design Return Temperature – 60^{o}C (appendix 3)
- Average Ambient Temperature – 15^{o}C (BRE)
- Pipework Material – Steel (appendix 3)

Table 7.26: Calculated Heat Network Distribution Heat Loss

HN Calculated Distribution Heat Loss					
Pipe Diameter	Measured Length	Insulation Thickness	Heat Loss per Metre	Total Heat Loss	Annual Heat Loss
mm	m	mm	W/m	Watts	KWh/yr
25	869.2	20	9.8	8,518	74,619
32	469	20	11.5	5,394	47,247
40	875.6	20	12.63	11,059	96,875
50	99.4	25	12.81	1,273	11,154
65	208	25	15.26	3,174	27,805
80	70.8	25	17.23	1,220	10,686
100	12	25	21.12	253	2,220
125	19	30	25.03	476	4,166
Total	2623	-	-	31,367	274,773

Table 7.27 presents the calculated DLF from equation 3. Additionally, DLF's were calculated based on the measured heat loss (table 7.26) and the different delivered energy data to compare the 'measured heat loss' with the 'predicted heat loss' to predicted performance in practice.

Table 7.27: Comparison of Distribution Loss Factors

HN Distribution Loss Fact (DLF)					
Dataset:	Energy Delivered (E_{del})	Heat Loss	Total Supplied Heat (E_{gen})	Annual Heat Loss	DLF
	KWh/yr	KWh/yr	KWh/yr	%	-
Actual	495,513	568,987	1,082,500	54%	2.18
SAP	697,896	64,549	762,444	9%	1.09
SAP*	563,083	52,110	615,194	9%	1.09
Actual^{+}	495,513	274,773	770,286	36%	1.55
SAP^{+}	697,896	274,773	972,668	28%	1.39
SAP*$^{+}$	563,083	274,773	837,856	33%	1.49

*Corrected for degree-days

$^{+}$ Corrected for calculated pipework heat loss (table 7.26)

The actual DLF was twice that predicated by the SAP. When the calculated assessment of DLF is applied to the different delivered energy, SAP, SAP^{+} and SAP*$^{+}$, the gap is significantly reduced in all instances. Furthermore, when the CS thermal demand (E_{del}) and the calculated assessment of the DLF are compared (Actual^{+}) to the predicted SAP*$^{+}$, the difference is very small. Therefore, the SAP assessment can estimate a reasonable HN performance if calculated assessment of the DLF are undertaken. However, the document analysis (chapter 6) identified that DLF is not routinely calculated for an ES. This identifies a point where an element of an EPG has been directly created by insufficient feasibility assessment. The results have shown that the CS HN could not have achieved the performance in practice defined in the ES or SAP assessment.

The difference between the calculated assessment of the DLF (Actual^{+}) and the performance in practice of the observed DLF (Actual), suggests that there would have still been an EPG. Although it is recognised that certain assumptions are made in the calculation of heat losses (e.g. ambient temperature), these are considered to have a minimal overall effect to the calculated losses. It is expected that the predominant cause of the gap is likely to be the result of common issues associated to the EPG as documented in previous industry and academic research in this field (section 4.2.3). This might include:

- Installation – e.g. design details not followed resulting in inferior or missing insulation.
- Commissioning – e.g. design parameters not achieved, such as flow and return temperatures.
- Operation – e.g. the quality of the insulation or maintenance of the system within the design parameters have not been maintained.

Relative Importance of Losses (RiL)

The RiL is the ratio of all energy consumed in the distribution of heat, divided by the energy delivered to all end consumers (figure 7.20). The RiL is defined by *equation 5* and requires the values for DHL (E_{loss}), AE (E_{aux}) and delivered heat (E_{del}).

The earlier findings identified an EPG exists for DHL and AE. Therefore, is not surprising that there is a difference in RiL. To evaluate the impact that AE (E_{aux}) and DHL (E_{loss}) has on the calculated RiL, the assessed figures for AE (13% of E_{del}) and DHL (table 7.27) have been applied to the datasets for comparison (figure 7.20).

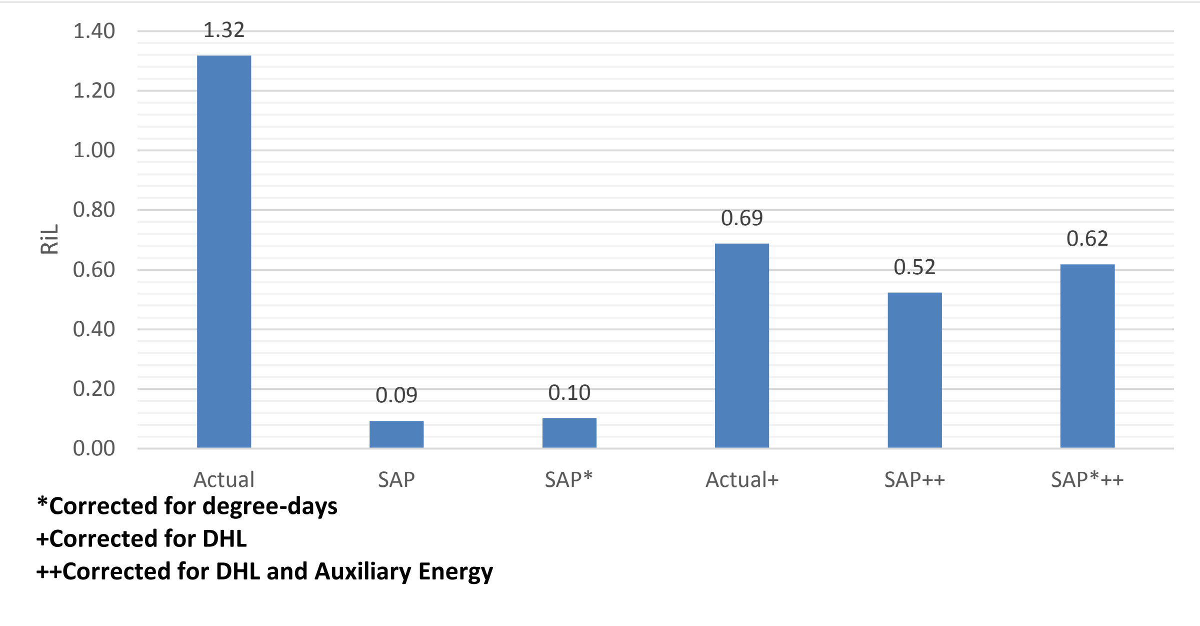


Figure 7.20: Relative Importance of Losses - Comparison of Corrected Figures

The results show that the current default figures applied in the SAP assessment are inadequate to predict the importance of energy losses of a HN. Where the energy losses are assessed (SAP^{++} and SAP^{*++}) there is a considerable reduction in the difference. However, the observed RiL (Actual) is still twice that of the predicted. It has been found that when the calculated assessment of the RiL ($Actual^{+}$) is compared to the predicted SAP^{*++}, the gap is found to be small (figure 7.20) and therefore a more reasonable estimate of energy use.

Primary Energy Efficiency (PEE)

The PEE takes into account the net useful energy generated by a HN-CHP, including electricity generated by the CHP. It compares the net delivered energy to the primary energy consumption. The PEE has been calculated for each dataset using *equation 6* (figure 7.21).

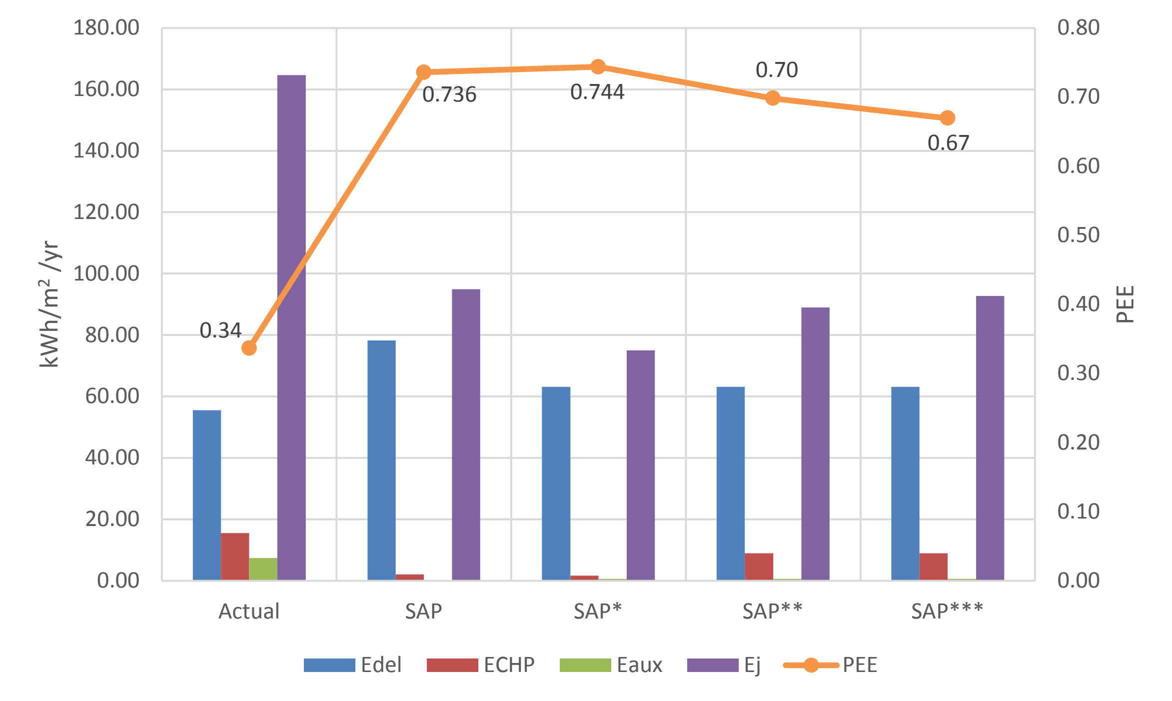


Figure 7.21: Comparison of Primary Energy Efficiency

The HN-CHP system has a substantially lower PEE (0.34) than predicted by the SAP (0.736) (figure 7.21). The gap is reduced marginally when site specific factors are included (SAP*, SAP** & SAP***). The results indicate that the E_{aux} and E_{loss} are the main factors influencing the difference in PEE, owing to their direct influence on primary energy consumption (Ej). The HN-CHP has been shown to have generated considerably more electrical energy than predicted in the SAP assessments. To understand the impact of the CHP, the PEE has been calculated for a HN *with* and *without* a CHP (figure 7.22).

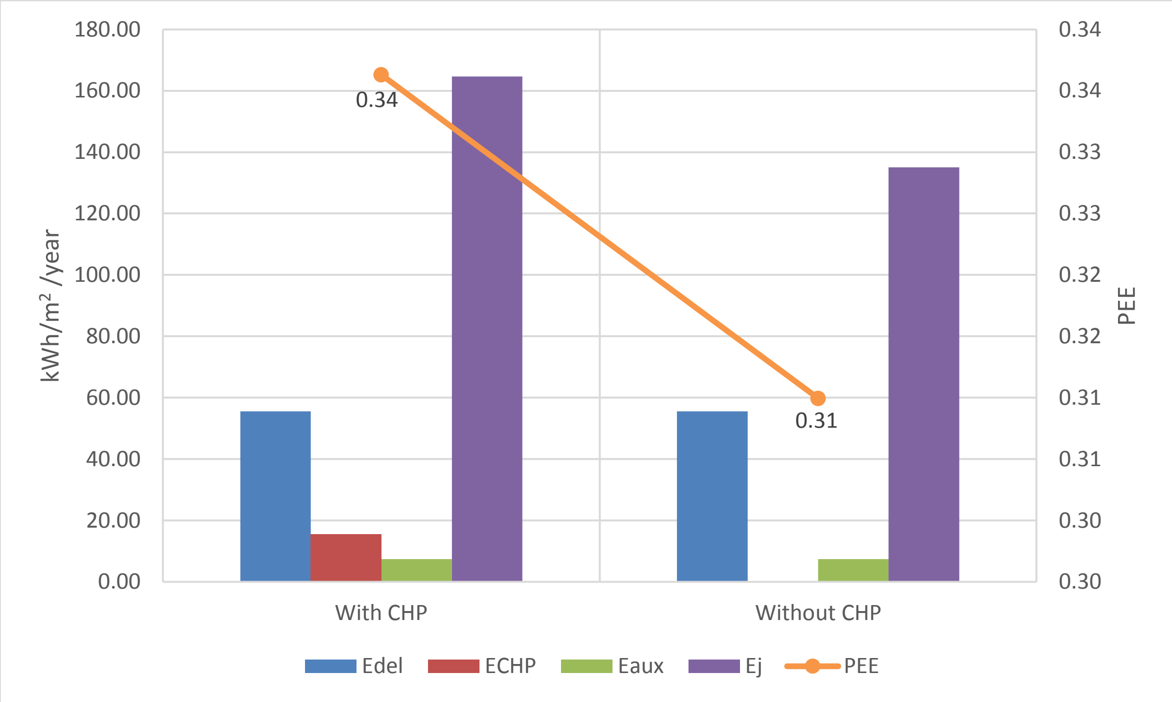


Figure 7.22: Primary Energy Efficiency *With* & *Without* CHP

The results have shown that the PEE is improved with the incorporation of a CHP. The generated electrical energy has a greater influence than the additional primary energy consumed by the CHP. The earlier analysis found that a HN-CHP delivers CO_2 saving compared to a HN *without* a CHP (section 7.4.4.2). These findings advocate the use of CHP in the HN. However, the economic impact has not been assessed by this method of analysis. Figure 7.22 identifies that primary energy consumption increases with the incorporation of a CHP and therefore primary energy costs increase. Furthermore, the generated electricity (E_{CHP}) exceeds the AE (E_{aux}) and therefore excess electricity would be exported to the national electricity grid.

Chapter three's earlier examination of CHP identified the difficulties that small generators face trying to export generated electricity to the energy markets (Hawkey, 2012; Kelly et al, 2010). The ES document analysis conducted (chapter 6), identified economics as a common motive for the adoption of CHP. However, the analysis also found that few (2%) included any form of economic assessment. Therefore, technical evaluation and arguments for CO_2 reduction can be made for the inclusion of a CHP, such as those presented in this CS. However, the viability is likely to be directly associated to economics. Table 7.28 presents a simple economic analysis (using a method adapted from Carbon Trust, 2004) of the CHP based on the predicted and actual performance. The following figures have been assumed for the analysis:

- Import Gas Price – 2.9p/kWh
- Import Electricity Price – 13p/kWh
- CHP Capital Costs – based on figure 3.9
- CHP Maintenance Costs – based on figure 3.9

Table 7.28: CHP Simple Economic Analysis

Energy Cost Savings			**SAP**	**SAP***	**Actual**
Heat Supplied	$E_{gen, CHP}$	MWh/yr	30,606	24,702	231,594
Displaced Thermal Fuel Savings	*2.9p/kWh*	£/yr	£944	£762	£7,472
Electricity Supplied	E_{CHP}	MWh/yr	18,893	15,248	138,679
Displaced Electricity Import	E_{aux}	MWh/yr	18,893*	5,631	66,225
Displaced Electricity Import Savings	*13p/kWh*	£/yr	£2,456	£732	£8,609
Total CHP Savings	-	£/yr	£3,400	£1,494	£16,082
Operational Costs					
CHP Fuel Input	$E_{j,CHP}$	MWh/yr	65,120	52,557	430,081
CHP Fuel Input Costs	*2.9p/kWh*	£/yr	£1,888	£1,524	£12,472
Maintenance Costs	Figure 3.20 (14p/kWh)	£/yr	£265	£213	£1,942
Total Operating Costs	-	£/y	£2,153	£1,738	£14,414
Financial Return					
Net Savings	-	£/yr	£1,247	-£244	£1,668
Capital Costs	Figure 3.19 (£1,300/kWe)	£	£45,500	£45,500	£45,500
Simple Payback	-	Years	36.48	-	27.28

*All CHP generated electricity utilised

The CHP payback period under all analysis scenarios exceeds the likely life expectancy of the CHP (table 7.28). For the predicted assessment (SAP and SAP*) the low output of the CHP does not provide a sufficient financial return to offset the capital costs. For the actual CHP over half of the generated electricity was exported. Consequently, insufficient primary energy savings were achieved. Therefore, the data available demonstrates that an early stage economic assessment would have shown that the CHP was not economically viable. It is expected that this gap between primary efficiency and an economic viability is likely to continue and grow more complex on the backdrop of the decarbonising of the electricity network and increasing electricity costs (for further information see Crane, 2018).

District Heating Global Efficiency (DHGE)

The DHGE is a simple ratio of all energies delivered and necessary energies of the HN-CHP system. Equation 7 was used to calculate the DHGE for each dataset (figure 7.23).

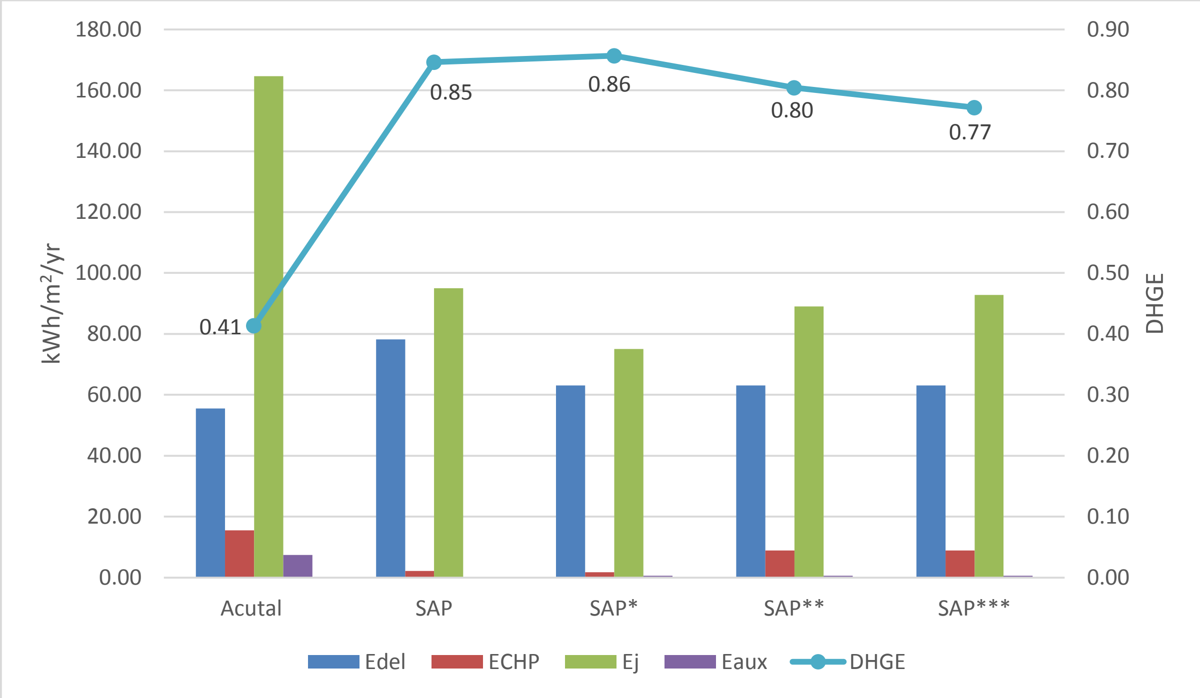
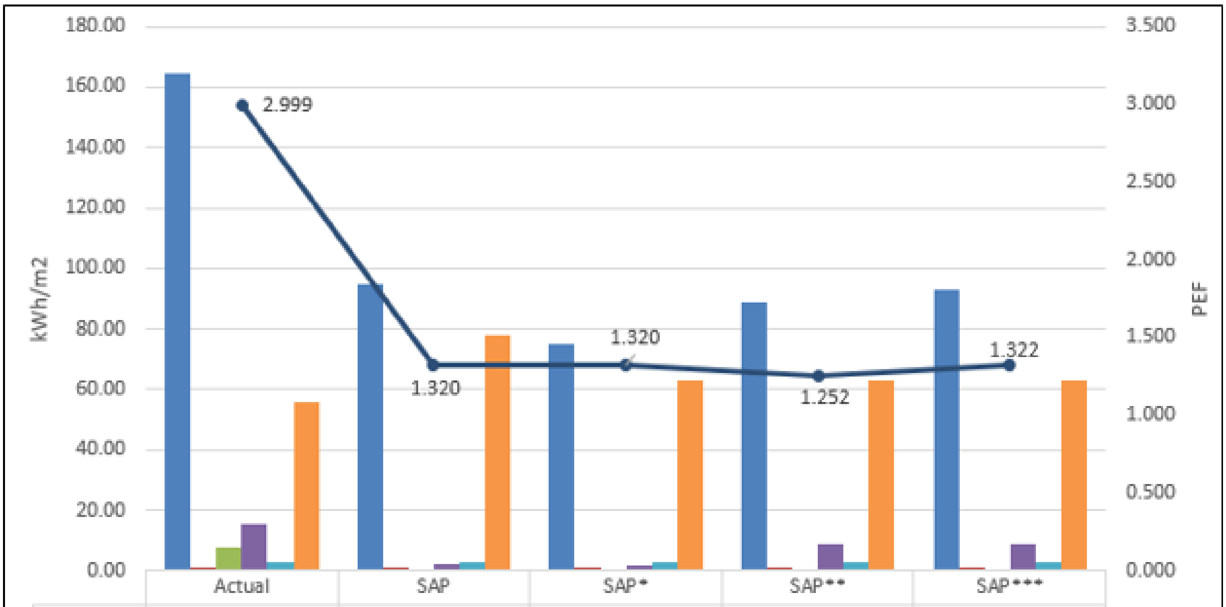


Figure 7.23: Comparison of the District Heating Global Efficiency

The results demonstrate that the HN-CHP system was only half as efficient as predicted. Where case specific conditions are taken into the consideration (SAP*, SAP** and SAP***) the DHGE efficiency decreases and the gap is reduced marginally. As seen with the other EPI, the DHL and AE are the prominent factors effecting the DHGE of the HN-CHP system.

Primary Energy Factor (PEF)

The PEF is the main parameter used in assessing a HN-CHP performance. It allows direct comparison in primary energy use between multiple technologies. It is an energy balance between the net energy delivered to the primary energy used (*equation 4*).



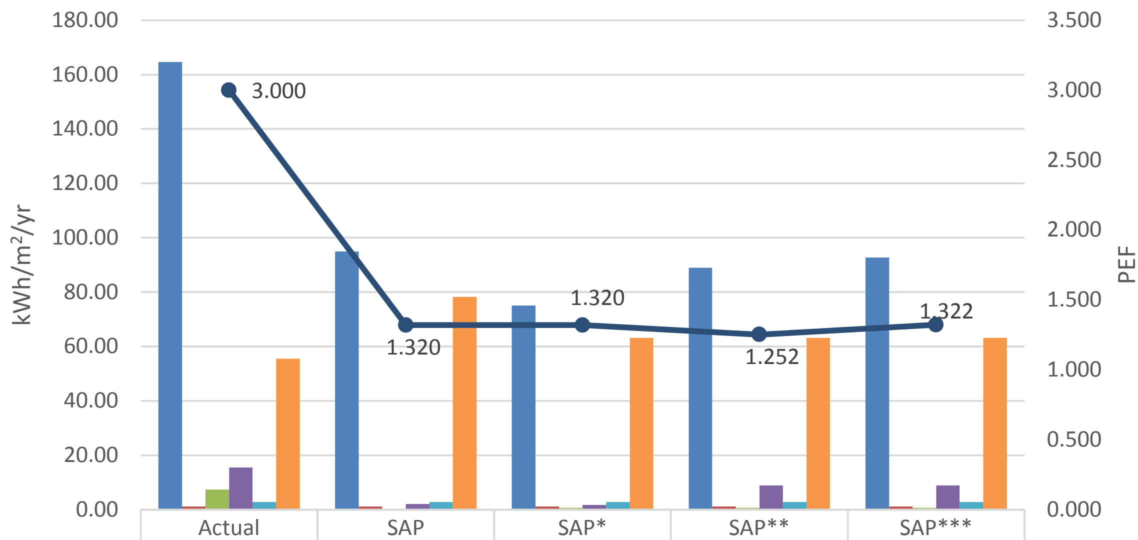
	Actual	SAP	SAP*	SAP**	SAP***
Ej	164.64	94.96	75.06	88.98	92.79
Fp,j	1.15	1.15	1.15	1.15	1.15
Eaux	7.42	0.00	0.63	0.63	0.63
ECHP	15.55	2.12	1.71	8.94	8.94
Fp,el	2.80	2.80	2.80	2.80	2.80
Edel	55.55	78.24	63.13	63.13	63.13
FpDh	2.999	1.320	1.320	1.252	1.322

*Corrected for degree days
**Corrected for degree days and thermal fraction
***Corrected for degree days, thermal fraction and thermal efficiency

Figure 7.24: Comparison of Primary Energy Factors

The observed PEF of the HN-CHP system is significantly worse, by a factor of 2.27, than predicted in the SAP (figure 7.24). The SAP** demonstrated the best PEF owing to the increased thermal fraction of the CHP and higher thermal efficiencies. Therefore, an EPG has been observed between the intended design and the performance of the HN-CHP system in practice. The significant increase in primary energy consumption, a consequence of high DHL and AE consumption, is the predominant cause of the EPG.

Figure 7.25 presents the analysis of the HN-CHP system compared to a range of conventional domestic gas boilers. The four domestic boiler types have varying thermal efficiency (section 7.4.4.1). Furthermore, to analyse the influence of the CHP on the PEF, a HN without CHP has also included (figure 7.25).



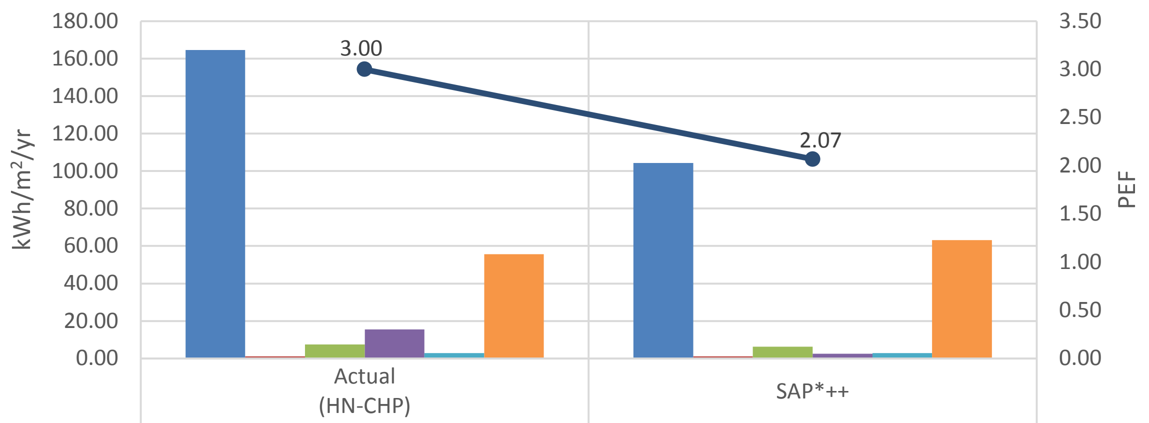
	Actual	SAP	SAP*	SAP**	SAP***
Ej	164.64	94.96	75.06	88.98	92.79
Fp,j	1.15	1.15	1.15	1.15	1.15
Eaux	7.42	0.00	0.63	0.63	0.63
ECHP	15.55	2.12	1.71	8.94	8.94
Fp,el	2.80	2.80	2.80	2.80	2.80
Edel	55.55	78.24	63.13	63.13	63.13
FpDh	3.000	1.320	1.320	1.252	1.322

Figure 7.25: Comparison of Primary Energy Factors – Heat Network (with and without CHP) and Individual Domestic Boilers (Type A, B, C and D)

The HN-CHP (3.00) has a lower PEF than a corresponding HN *without* CHP (3.17), owing to the positive primary energy offset from generated electricity. This corroborates the phenomenon described by Pacot and Reiter (2011), that LZC technologies, such as CHP, can obscure the inefficiencies of a HN; although in this specific case the difference was relatively small. The examination of the other EPI, as presented in this CS, are therefore critical to identify the underlying performance of a HN and identify specific areas of inefficiencies.

The analysis also demonstrates that domestic gas boiler systems have a lower PEF than the HN-CHP system. Boiler type C (BT-C) has the lowest thermal efficiency (69%) and it still has a significantly lower PEF than the HN-CHP system. However, the SAP predicted PEF (1.32) is below that of the highest efficiency domestic gas boiler (BT-B: 1.38). Therefore, under the SAP predicted performance a HN-CHP system could be justified, but not reflective of achievable performance in practice.

HN's are championed by academia and professional industry to offer a more efficient method of providing heat to residential buildings. However, the findings of this case have demonstrated that all necessary energy consumptions of HN (especially, DHL and AE) can significantly influence performance in practice and outweigh potential positive efficiency gains from large scale gas boilers and LZC technology (e.g. CHP). Furthermore, this is critical to understanding a common justification of a HN; that a HN provides an opportunity to ‘future proof’ a development for integrating LZC technologies (chapter 6). The evidence presented in this CS has demonstrated that unless the true necessary energy consumption of HNs are understood, calculated and evaluated, the ability of a future LZC technology to deliver energy and CO_2 reductions in practice are significantly undermined.



	Actual (HN-CHP)	SAP*++
Ej	164.64	104.34
Fp,j	1.15	1.15
Eaux	7.42	6.31
ECHP	15.55	2.56
Fp,el	2.80	2.80
Edel	55.55	63.13
FpDh	3.00	2.07

***++Corrected for degree-days, DHL and AE**

Figure 7. 26: Comparison of Observed Primary Energy Factor and Predicted Primary Energy Factor

When the calculated DHL and AE are utilised as part of the SAP* predicted performance (figure 7.26), the PEF is lowered from 3.00 to 2.07. The PEF difference between the SAP (1.32) and the SAP*++ (2.07), represents a significant proportion of the observed EPG that can be directly related to the assessment method applied to predict the performance of DHL and AE.

7.5 Case Study Findings

The purpose of the CS was to examine if an EPG could be observed, and where so, to identify the specific elements of the HN-CHP system where an EPG exists. Key EPIs were identified to judge the existence of an EPG. The ES document presented both professional opinion and quantitative justifications for the selection of a HN and CHP. Firstly, it was stated that larger commercial type gas boilers would have a high thermal efficiency (94%). But in practice the analysis found that the average efficiency of the gas boilers over the reference year was 81.93%. The gas boiler efficiency did increase in relation to a higher fraction of thermal load, the highest efficiency was observed to be 89.88%. Therefore, it was found that the predicted thermal generation efficiency of the gas boilers was not achieved in the reference year and a performance gap exists. Furthermore, the results suggested that thermal efficiency could be directly related to thermal fraction of heat demand and therefore suggests variations in efficiency should be considered when designers are considering multiple heat generating technologies, including future LZC technologies as part of a HN.

The second performance indicator was to determine if the HN system delivered a CO_2 saving of at least 52,515 kgCO_2/year, compared to an alternative heating method (individual domestic gas boilers). A comparison was made for a range of theoretical domestic gas boiler efficiencies (69%-83%). The results found that the HN emitted twice as much CO_2, than even a comparatively low efficiency individual domestic gas boiler. The significant energy and CO_2 associated to the DHL and AE, outweighed the savings achieved from higher thermal efficiency of the larger communal boilers.

The other two performance criteria identified from the ES document related to the performance of the CHP. It was expected that the inclusion of a CHP would save 28,334 kgCO_2/year, equal to a 9% CO_2 saving compared to a HN without a CHP. The analysis found that the CO_2 savings attributed to the CHP in the reference year was 27,512 kgCO_2, equivalent to a 10.52% saving. Therefore, the design justification for a CHP proposed in the ES was confirmed. Although the CO_2 saved was slightly less than predicted, the overall savings exceeded the percentage reduction prediction. It is noted that these results are based on the Part L 2006 emissions factors for gas and electricity, if the most recent emissions factors were applied the CO_2 benefit would be less.

The SAP assessments were analysed and evaluated against the observed performance in practice of the HN-CHP system. The number of degree-days within the reference year were found to be lower than presumed in the SAP methodology. Therefore, a secondary SAP dataset was created, that adjusted the SH demand (SAP*).

It was found that the HN-CHP consumed more energy and emitted more CO_2 in practice than predicted. The key findings from the analysis of the EPI is that the majority of the EPG can be directly attributed to the poor performance of the HN system. The domestic thermal demands (E_{del}) were less than predicted, while the primary energy (E_j) was significantly higher than predicted. The significant factors creating the EPG were found to be the DHL (E_{loss}) and the AE (E_{aux}).

The results, specifically for the reference year, found that the energy prediction method in the SAP* assessment provided a reasonable prediction of domestic SH and DHW demand. The lower observed domestic thermal demand could be attributed to the occupants influence on energy consumption or secondary heat (e.g. warming of building fabric from HN distribution heat losses). This is supported by the significant variation observed in consumer energy demand between dwellings of similar type.

The secondary purpose of the CS was to examine if a more realistic expectation of performance in practice could be provided by the defined EPI. The results found that the SAP*, specifically for the reference year, provided a reasonable estimate of HD and LHD. HD as an early stage indicator of the HN feasibility, was shown for all datasets to be higher than the GLA minimum threshold. Therefore, in terms of GLA policy, the building would be considered potentially suitable for a HN. However, the detailed analysis demonstrated that seasonal heat demands have a significant influence on HD. Examination of the HN circuits, identified that HD varied considerably with time of year and could be below the GLA threshold during milder months. These findings suggest that feasibility assessments should consider a range of seasonal conditions, including potential changes due to climate change.

The analysis of LHD exhibited that it was relatively low compared to the range of LHD presented in the earlier examined industry and academic guidance. Furthermore, the examination of the SAP predicted LHD, found that the corresponding DHL was unrealistic compared to observed performance of operational European HNs. Therefore, it was found that evaluation of the predicted LHD would have been an early indicator of DHL in practice and that the SAP predication would likely be exceeded.

The DLF of the HN was measured and analysed to determine if the scale of losses could have been predicted and included in an early stage feasibility assessment. A significant variation between the SAP DLF (1.09), the calculated DLF (1.73) and the actual performance (2.18) was observed. The calculated DLF provided a significantly better indication of the observed DLF. Therefore, it was found that a more realistic estimate of DLF could be calculated, including during early stage feasibility assessment. Finally, the identified difference between calculated and observed DLF is expected to be prominently the result of common installation and operational issues associated to the EPG.

The PEF was used to provide an independent assessment of the overall EPG. The findings demonstrated that the observed PEF was significantly worse than that intended (SAP). The results also demonstrated that the CHP has a positive effect on the PEF, owing to the positive influence of CHP generated electricity. However, potential economic issues relating to the CHP were identified, demonstrating that economic as well as technical feasibility is crucial to early stage feasibility assessment. The other performance indicators (RiL, PEE and DHGE) have identified that high DHL and AE consumption were the primary cause of the worse PEF. The findings supported the research by Pacot et al (2011), that PEF can obscure inefficiencies in HN. The examination of the other EPI was found to be critical to identifying the underlying performance of a HN-CHP system. Finally, when the calculated DLF and AE are included in the assessment, the EPG is lowered. Therefore, effective assessment of the EPI at an early project stage would have identified a more reliable expectation of performance in practice. A meaningful proportion of observed EPG is related to inadequate assessment methods.

A further discovery of the analysis is the observed PEF and the calculated PEF (based on EPI) were significantly worse than a range of theoretical domestic gas boilers. This demonstrates that the adoption of a HN-CHP can result in increased energy and CO_2 compared to a standard heating system, the opposite of the ES intention.

Figure 7.26 demonstrates via a Sankey diagram the major energy transfers and flows within the case study HN-CHP system.

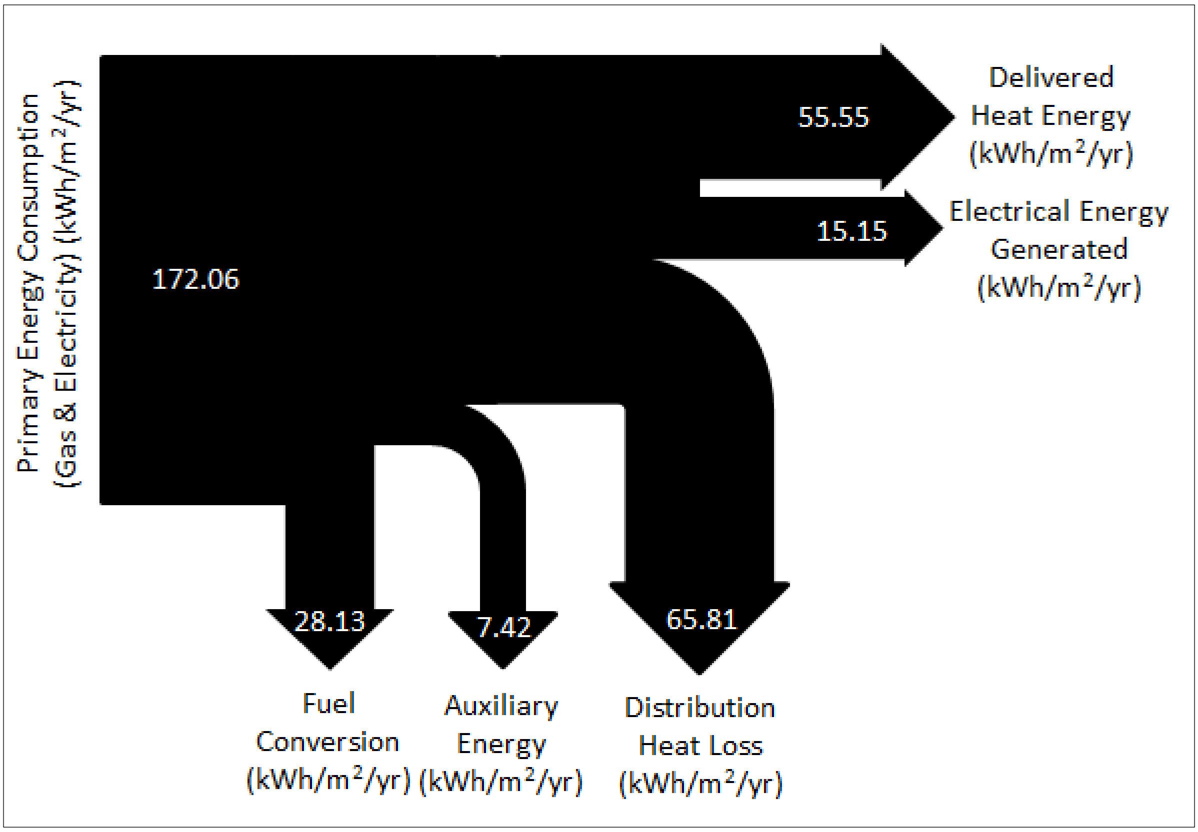


Figure 7.27: Case Study Sankey Diagram of the HN-CHP System Energy Flow

The CS has also provided a critical view to understanding one of the common justifications for the selection of a HN, to 'future proof' a development for integrating LZC technologies (chapter 6). It is clear from evidence presented that unless the true necessary energy consumption of HN are understood, calculated and evaluated, the ability of a future LZC technology to deliver energy and CO_2 reductions in practice is significantly undermined.

7.6 Chapter Reflectance

This chapter has provided a systematic analysis of the energy consumption and resulting CO_2 for the provision of domestic SH and DHW via a HN-CHP system in a residential building. The performance of the HN-CHP system was evaluated against the design intent defined in the planning stage ES and designed SAP performance assessment. The CS did not review the energy consumption that was not directly related to the provision of domestic SH and DHW (i.e. lighting, ventilation) or unregulated energy loads (i.e. cooking, appliances).

The evidence presented in this chapter has demonstrated that:

- An EPG was observed between the design intent and the performance in practice.

- The professional opinions that justified the selection of a HN were demonstrated to be in consistent with observations in practice. However, the CHP was found to provide a positive contribution to CO_2 reductions, consistent with the common perspectives.
- The greatest influence on the scale of the EPG was observed to be the high energy consumption of the HN compared to the intended design.
- The DHL and AE associated with the HN, were found to be the prominent differences between the design intent compared to the performance in practice.
- A meaningful proportion of the observed EPG has been directly linked to inadequate feasibility assessment.
- It is expected that early stage assessment of the defined EPI would likely influence the motives and decision to select a HN-CHP before/instead of other technologies.
- Unless the true necessary energy consumption associated with HNs are understood, calculated and evaluated, the ability of 'future' LZC technologies to deliver energy and CO_2 reductions in practice could be significantly undermined.

CHAPTER 8: A SURVEY OF ENERGY CONSULTANTS

This chapter details the development of the questionnaire and reflects on the data gathered. The purpose of the questionnaire is to gain from industry professionals their opinions and perspectives regarding the adoption of local planning energy policy; methods for assessing LZC technologies; and the EPG in HN-CHP systems. The views obtained will provide an understanding of the wider experience across the professional practice. The chapter concludes by reflecting on the evidence obtained and how it answers the research questions.

8.1 Ethical Considerations

All researchers need to consider ethical principals when completing their research to ensure that they are proceeding in a responsible and morally defensible way (Gray, 2013) . Qualitative research owing to the close interactions with the participants can pose particular ethical problems.

To maintain a morally defensible stand point, the information attained in this research must not cause harm or be gained via deception to the participants. As such, a normative approach will be used in this research following a deontological perspective. This focuses on the rights of the participants and that the 'ends never justify the means'. Gray, (2013, p.68) identifies two conflicting views on this perspective, universalistic (rules and principles should never be broken) and contingent (duties may vary across different contexts). The research design requires concurrent data collection and therefore consistency in research approach is required. This must also apply to the ethical approach and therefore a universalistic view will be taken. Gray, (2013, p.90) provides a checklist of ethical issues. Table 8.1 defines these and states what actions will be taken to avoid this potential ethical issues.

Table 8.1: A Checklist of Potential Ethical Issues and Actions Taken to Avoid (adapted from Gray, 2013, p.90)

Ethical Issue	**Description**	**Action Taken**
Privacy	The right not to participate and to withdraw at any time.	Participants are required to agree to participate by selecting to 'Begin the Survey'. A participant can withdraw at any time by closing the web browser. Incomplete surveys will be discounted.
Promises and Reciprocity	What do participants gain from cooperating with the research? If promises are made (e.g. copy of the final report, charitable donation) these should be kept.	A financial donation was made to a charity following the completion of the survey. A final electronic copy of the thesis will be provided to any participant who requests it.
Risk Assessment	In what ways will the research put people under psychological stress, legal liabilities, ostracism by peers or others? How are these risks dealt with?	Participation in the survey is kept strictly confidential. Participants are only asked questions regarding their experience from their professional practice. No specific details are requested (e.g. company names, project names, project contacts) and any provided will be anonymised.
Confidentiality	What constitutes the kinds of reasonable promises of confidentiality that can be honoured in practice?	Participants' information (e.g. name, email address, contact details) are not shared and stored on a secured cloud storage system. On completion of the research the information will be deleted.
Informed Consent	What formal consent is necessary and how will it be obtained?	Participants are required to agree to participate by selecting to 'Begin the Survey'.
Data access and ownership	Who will have access to the data and owns it?	Only the research author and Supervisor have access to the data. The data is owned by the author.
Researcher mental health	How will the researcher be affected by conducting the research?	The researcher is working within his own professional practice.
Advice	Who will the researcher use as a confidante on issues of ethics during the research	Research supervisor and the department's ethics committee.

The Department of Engineering has a four stage ethical review process. The first stage is a self-assessment carried out by the researcher in a consultation with the research supervisor. The aim of this assessment is to consider whether any ethical concerns are raised. If there are no ethical concerns, the researcher may proceed. Stage two is required if the research project involves human participation. The researcher considers the potential risk of harm to the participants to be minimal, it may be appropriate to seek 'light-touch' review from the respective Divisional Representative who can give guidance on whether the application can proceed with or without further review. The self-assessment (table 8.1) has evaluated that there is no ethical concerns. However, as the research includes human participation a 'light-touch' review was sought and granted from the respective Divisional Representative. The ethics approval letter is available in appendix 6.

8.2 Questionnaire Design

Arksey and Knight (1999) identify a number of areas to avoid when constructing questionnaires. These include prejudicial language, leading questions, and assumptive or hypothetical questions. This questionnaire used 'closed' 'Rank' and 'Scale' type questions designed on the Likert scale for ease of answering and reviewing data (Oppenheim, 1992). However, closed questions do lose 'spontaneous responses' and can lead to bias in the answer categories (Oppenheim, 1992 and Gray, 2013). In an attempt to balance the response structure a 'Comment' answer box was included within the questionnaire to enable respondents to add further information beyond the closed question.

The questionnaires have been constructed using a web based survey platform 'Survey Monkey'[14]. This platform was used as it is familiar within the professional practice. An email was sent to respondents with an access link to the questionnaire, this method was chosen as it enabled respondents to be specifically targeted. The platform has multiple outputs for the collected data, a downloadable 'CSV' file was used so results could be analysed and presented in various forms. The software facilitated the construction of a scale type ordinal questionnaire using the Likert scales, which solicit opinions ranked on a range of scales (Gray, 2013). This type of question was selected as it enables opinions to be examined against a range and to extract an overall opinion. However, to achieve this, Arksey et al (1999) suggest that the questions must be clear, concise and unambiguous, and avoid leading, assumptive or double meaning questions (Gray, 2013, p.340). Therefore, as observed by Foddy (1993) and Gray (2013, p.346), the questionnaire must 'cover the research issues that have been specified' and allow the respondent to interpret the question in the way the researcher intended. The questions have been posed to address four key themes (table 8.2).

[14] Survey Monkey: www.surveymonkey.com

Table 8.2: Questionnaire Themes

Theme: Credibility Gap	The questions will establish if, in the view of designers, there is a difference between predicted CO_2 reduction within an ES and CO_2 reductions achieved once built. This is important for the research as it identifies if and to what scale industry professionals believe, whether actual or perceived, that predicted CO_2 reductions are being realised in practice.
Theme: Drivers of Decisions	The questions will validate and build on the document analysis (chapter 6), the drivers influencing the selection of HN and CHP as well as other RE technology. This is important for the research as it identifies if the prescriptive based policy of TLP (e.g. Energy Hierarchy) is influencing the selection of technologies over, or in place of, appropriate technical appraisal. This will also identify to what level planning and industry guidance is being utilised by designers when they are forming an ES.
Theme: The role of an Energy Strategy in a project	The questions will determine what importance is attributed to an ES in the project and how it is utilised through the different stages of a project. This is significant for the research as it identifies to what level the ES can influence the design and construction of a development. Furthermore, who in the project process is believed to be ultimately responsible for the successful delivery of the ES.
Theme: The Energy Performance Gap	The questions will gain opinions from the industry professionals on the potential causes of the EPG and if local energy policies (e.g. TLP) are delivering the CO_2 reductions that are claimed.

Foddy (1993) warns that the process can break down in several areas which can threaten the validity of the questions asked. Therefore, it is important to trial the questions and review the suitability of the questionnaire for the respondents' demographic. Gray (2011) suggests that this will increase confidence in the interpretations of the questions and the respondents' willingness to provide answers.

8.3 Findings of Pilot Questionnaires

As observed by Gillham (2000), questionnaires need to be piloted to ensure understanding. Consequently, a pilot questionnaire was tested and evaluated with a focus group which commented on question content, instructions and relevance. Piloting the questionnaire ensured that it had the highest probability of completion and relevance to the research questions.

The pilot questionnaire was circulated to a small selection of participants within the author's professional practice, who also formed the focus group to test the ease of completion and the ability to extract data from the responses. The platform provided 'live' feedback regarding the number of completed, partially completed and incomplete questionnaires. The invitation email hosting the access link to the questionnaire was also tested and feedback on the instructions and welcome text fed into the main survey structure.

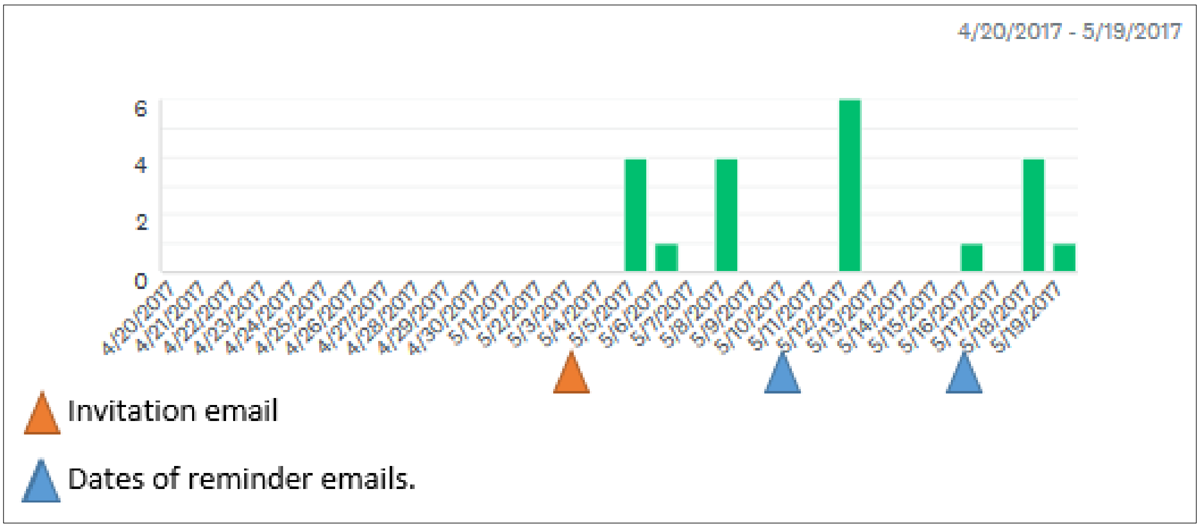


Figure 8.1: Pilot Questionnaire Response Rates

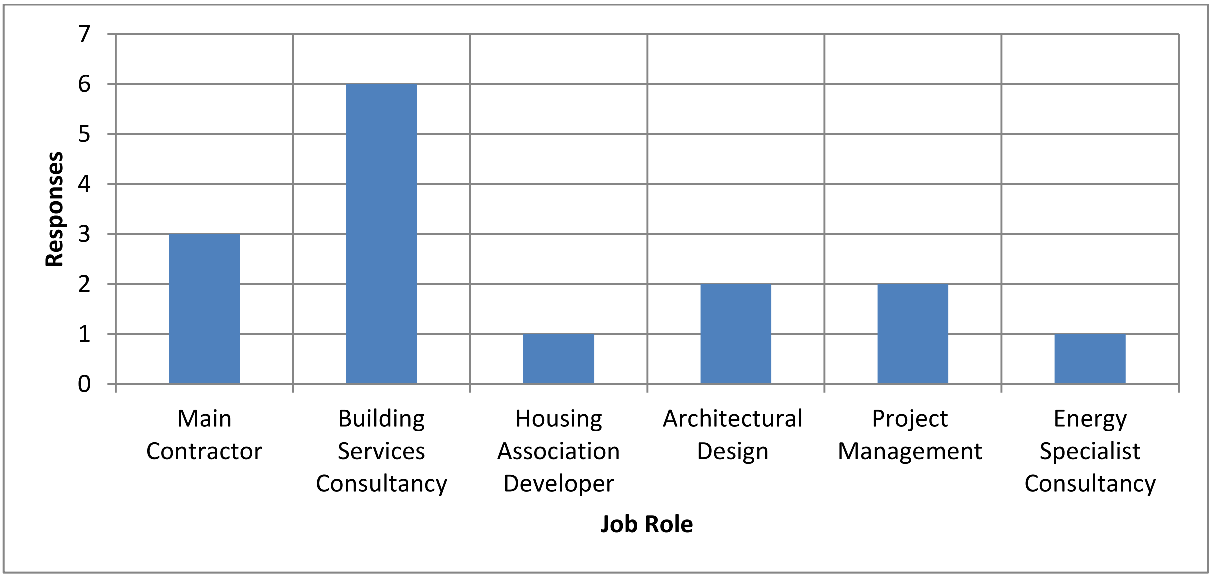


Figure 8.2: Pilot Questionnaire Job Roles and Number of Respondents

There were two prominent issues reported by the results of the pilot questionnaire and focus group. Firstly, many of the respondents, primarily those who did not classify themselves as engineers or energy consultants, found that they had insufficient experience to answer many of the questions or the questions did not relate to their work. Secondly, some of the questions were too long and contained too many statements. Further feedback related to the structure of some of the questions to allow simpler response: the requirement for a ‘Don’t Know’ option in some questions (Q9, Q10 & Q16) and some ambiguity in the wording of the questions (Q4 & Q5).

The results of pilot and focus group feedback exposed an initial tendency to ask a complex array of questions to a wide range of professionals without first considering how the information would be used. This directed the review of questions and respondent demographic back to the test criteria suggested by Gray (2013 p.346) ‘*is the question necessary?*’ and ‘*how will it be useful?*. The questions were restructured for the formal questionnaire to relate specifically to the themes presented in table 8.2. Furthermore, the narrowing of the respondent demographic to those directly involved in the professional practice of creating an ES, and the detailed design or the in-use analysis of HN-CHP. Arksey et al (1999) observe that questionnaires can generate insightful data when the people questioned have direct knowledge of the research area. In this case, the formal questionnaire was circulated to a specific range of professionals described below.

Conducting the pilot has been the successful trial of the online platform. Gillham (2000) and Gray (2013, p.359) observe that the questionnaire is a ‘one shot’ attempt at data gathering and as such the pilot study has assisted in improving the quality of the content, and therefore, assisted in the eventual response rate to the formal questionnaire.

Focus group note are included in appendix 7.

8.4 Formal Questionnaire Structure

The distribution list for the questionnaire was derived from multiple sources: an extensive online register[15] published by CIBSE for registered accredited assessors (e.g. Low Carbon Consultants, Heat Networks Consultants, and Low Carbon Energy Assessors); the authors and organisations identified through the ES document analysis; a search of related professionals through the online networking platform ‘Linked-In’; and existing contacts known within the author’s own professional practice. It was considered crucial to establish the type of organisation and job role of the respondents. Therefore, the initial questions clarified each respondent’s type of organisation, their professional job title and the duration of their professional experience. This allowed the data to be analysed based on experience and job role, but also eased the respondents into the questionnaire.

[15] CIBSE Assessor Register: https://www.cibsecertification.co.uk/Online-Register/Search-For-An-Assessor

The invitation email was sent to 234 contacts. A total of 73 responses were received, a return rate of 31%. Of the returns, 11 were found to be only partially completed. Gray (2011, p.363) argues that there are ‘two threats to the validity of questionnaires’, namely incorrect completion and non-responses. Oppenheim (1992) also suggests that the best approach to dealing with missing data is ‘not to have any at all’ Gray (2011, p.456). To improve the validity of the data and research findings, the non-completed questionnaires were removed, reducing the response rate to 62 (26.5%). There were a few undelivered invitations, 88 (36.9%) of the invitation emails were never opened. It is suspected that some of these emails were either automatically filtered or manually deleted by the recipient before opening. Removing these undelivered invitations has a response rate of 41%.

The questionnaires were sent and a four week response period was given. Saunders, Lewis & Thornhill (2007) list six techniques for improving questionnaire response rates, the most relevant being clear instructions, follow up communication and additional follow ups if response rates are low. The initial contact email and ‘welcome page’ were an important element for maximizing response rates (appendix 8). This is also observed by Cohen et al (2000) and Gray (2011) who suggest that clear and concise instructions throughout the questionnaire greatly increase the probability of response.

The response rate was monitored via the live feed-back online platform. Four reminder emails were sent to prompt for questionnaires to be returned. The response rate increased after each reminder email (figure 8.3). A final e-mail was sent to close the response period, to thank all the respondents and to confirm the charitable donation (appendix 8). A copy of the full questionnaire is included in Appendix 8.

On reflection, the response rate could have been higher if the distribution list had been more rigorously validated. Furthermore, some secondary contacts did not respond to the questionnaire, a prior telephone conversation with the secondary contacts may have increased the response rates. Despite this, the response rate from the industry professionals reflected the desire to engage with the research topic in the industry.

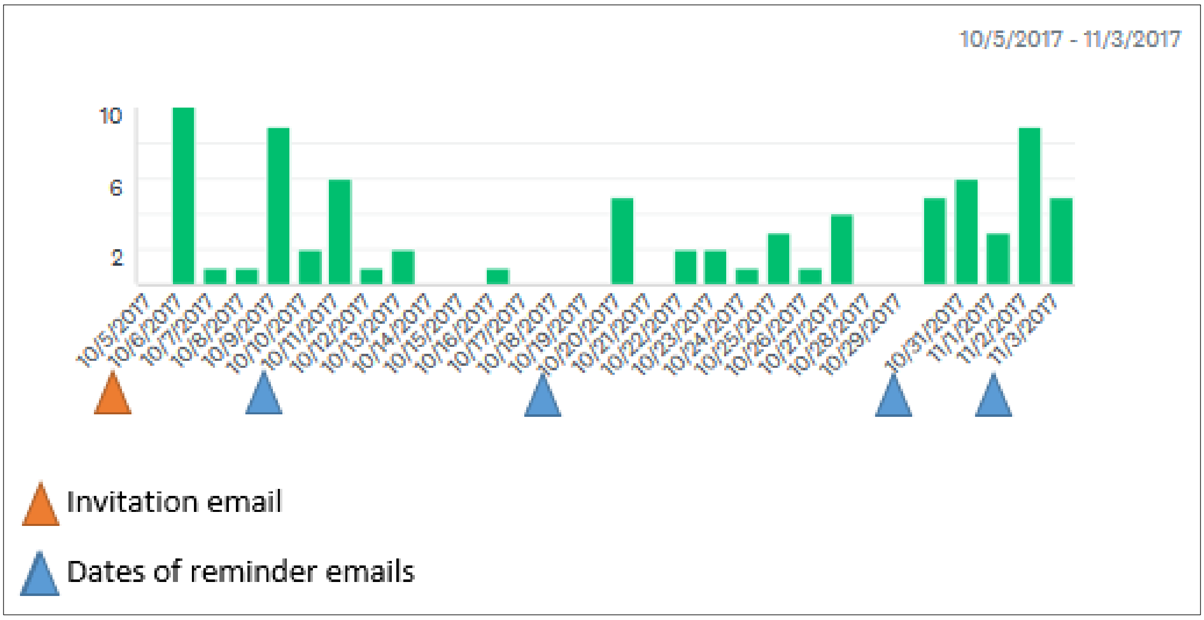


Figure 8.3: Questionnaire Response Rates

8.5 Questionnaire Responses and Results

The data that was converted to a 'CSV' file was organised and analysed (see sample excel data sheets in appendix 9).

8.5.1 Method for Data Analysis

Analysis was carried out based on nominal and ordinal descriptive statistical analysis. The questions were based on a 'Likert' scale, which comprises ordering and ranking of values based on a selection of pre-set questions (Blaikie, 2003). However, the intervals between the values (e.g. Strongly Agree, Agree, Neither Agree nor Disagree, Disagree, Strongly Disagree) are not intended to be of equal value.

8.5.2 Respondents Experience, Education and Training

Respondents were predominantly involved in the professional practice of energy and design consultancy (figure 8.4 and 8.5). The pilot questionnaire identified that in order to maximise the completion of the questions the respondent's required relevant experience. Therefore, the questionnaire was targeted at this particular group.

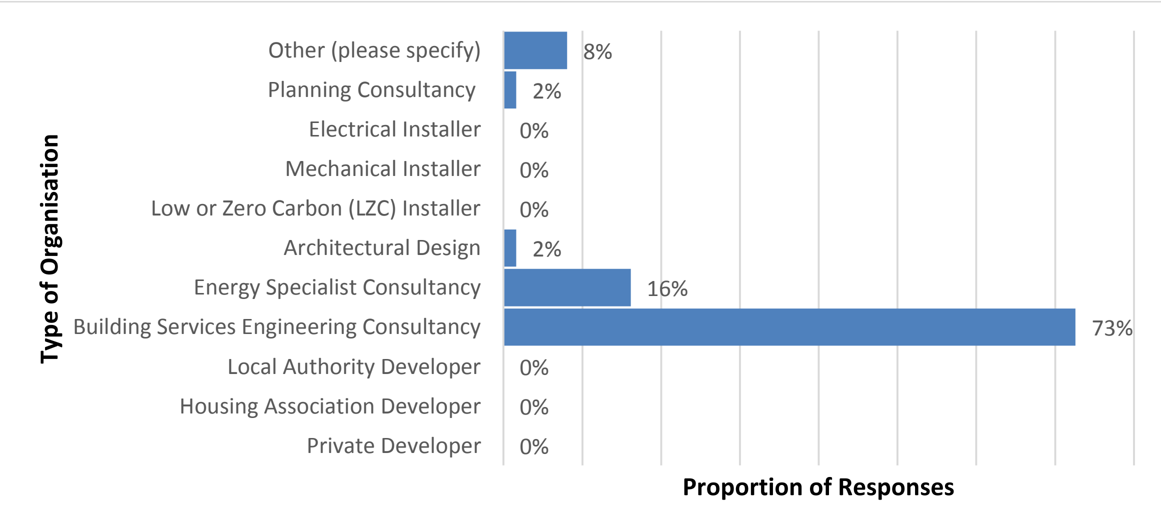


Figure 8.4: Respondents Type of Organisation

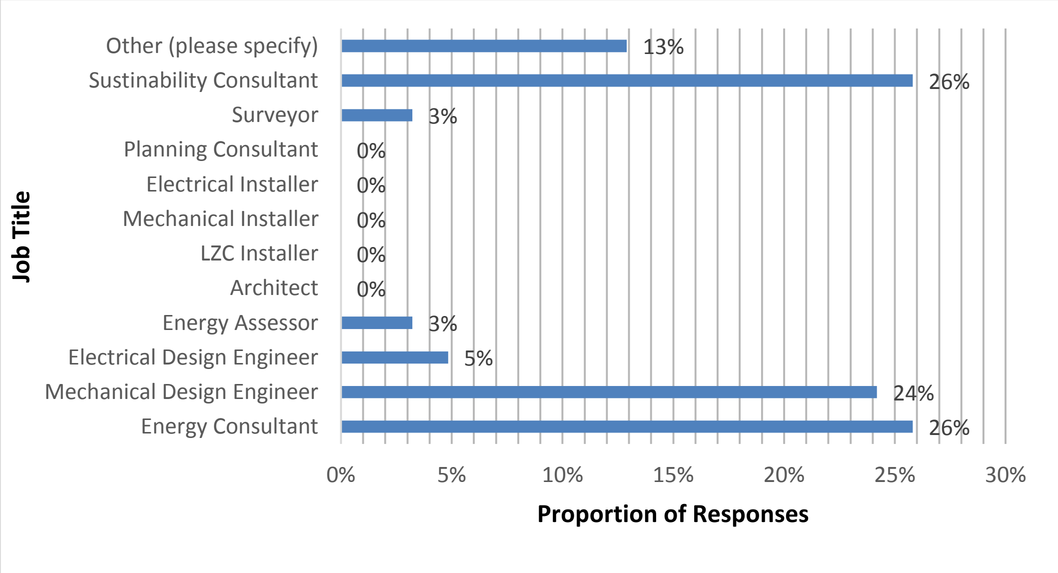


Figure 8.5: Respondents Job Title

All respondents have at least one years' experience (figure 8.6). Over half had more than 5 years' experience, which extends prior to the current iteration of TLP (2011 and 2016). A third of respondents had sixteen or more years' experience, which extends before the first publication of TLP (2004). Overall, the respondents have a broad range of experience with TLP and its evolution, including the shift in priority to HN-CHP.

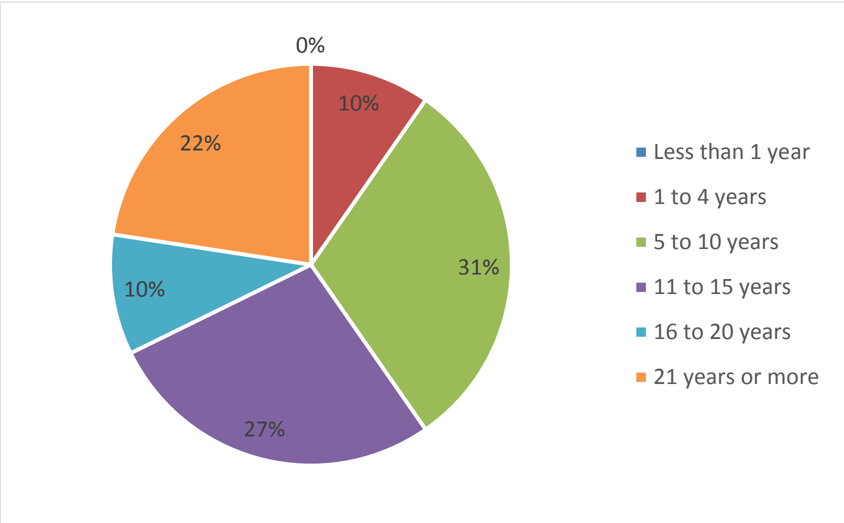


Figure 8.6: Years of Professional Experience

A question was posed to gain understanding what education and training forms part of the respondent's knowledge base (figure 8.7).

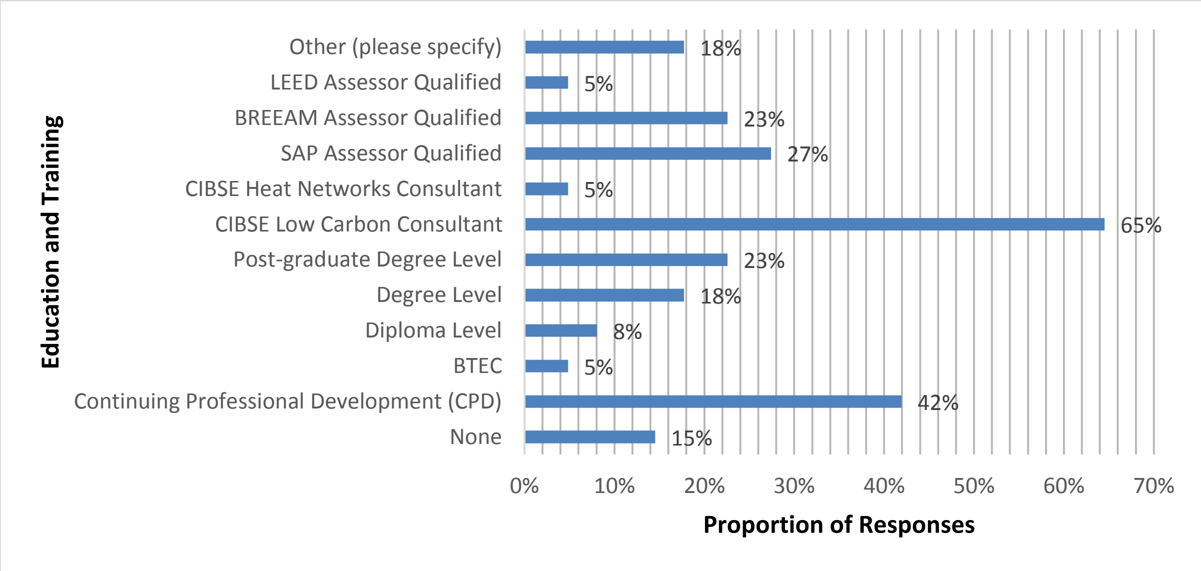


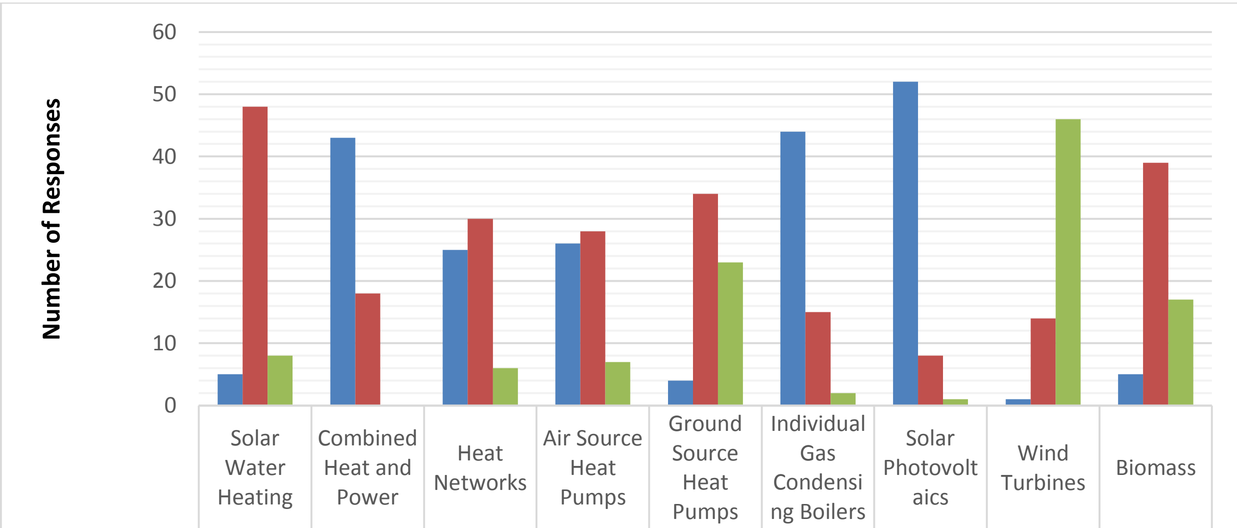
Figure 8.7: Education and Training in LZC Technologies

The majority of the respondents have had some formal industry lead training, whether by CIBSE or technical seminars (CPD). Almost two-thirds of the respondents were trained as a CIBSE 'Low Carbon Consultant' (LCC). CIBSE (2017), states that LCC are *'competent to minimise energy use and carbon emissions from buildings both in design and operation'*. The LCC design training consists of two days training with an 'industry expert'. There is no minimum entry requirements for previous education (e.g. engineering degree) or training. Examination of the LCC competency criteria identifies that the design course is predominately related to the EU (*Energy Performance of Buildings Directive)* and England and Wales (*Approved Document L: Conservation of Fuel and Power*) legislative requirements (ibid). There is no competency related to the design of LZC technologies, including HN and CHP, and more specifically the feasibility assessment of these technologies.

Over a third of respondents reported that they had training via CPD. CPD are typically short (lunchtime) technical presentations or seminars that are manufacturer lead. Manufacturer seminars can often be product specific and sales lead. Therefore, the level of unbiased knowledge transfer relating to the viability of a technology might be low.

There is less formal academic education undertaken by the respondents. This could be related to the number of respondents with over 11 years of experience, as low carbon construction and related planning policy has only been a prominent part of the industry for upward of 14 years. 35% of respondents that have greater than 11 years' experience, had some form of academic education (i.e. BTEC, Diploma, Degree, Post-grad degree). Whereas, 60% of respondents that stated they had less than 11 years, have some form of academic education. Heffernan, Pan and Liang (2012) found knowledge gaps and a low level of skills as prominent barriers to the delivery of low carbon homes. This survey identifies a prominence of short duration industry training based on legislative compliance and manufacturer sales promotion that might be feeding into, not closing, the skills and knowledge gap.

Figure 8.8 represents the level of experience the respondents have with different LZC technologies. Although not a 'LZC', individual gas condensing boilers were included as these are a prominent technology adopted. The respondents were asked to rank their level of experience using technologies to understand which are most prevalent. The respondents have extensive experience of photovoltaic and CHP while ground source heat pumps, solar water heating, wind power and biomass were least familiar. This spread of experience reflects Day's findings relating to the uptake in LZC technologies (Day et al, 2009a).



	Solar Water Heating	Combined Heat and Power	Heat Networks	Air Source Heat Pumps	Ground Source Heat Pumps	Individual Gas Condensing Boilers	Solar Photovoltaics	Wind Turbines	Biomass
Exstensivley	5	43	25	26	4	44	52	1	5
Limited	48	18	30	28	34	15	8	14	39
None	8	0	6	7	23	2	1	46	17

Figure 8.8: Experience with LZC Technologies

Figures 8.9 demonstrates which professional services the respondents have undertaken. These three specific professional services were asked as they relate directly to the key areas of this research.

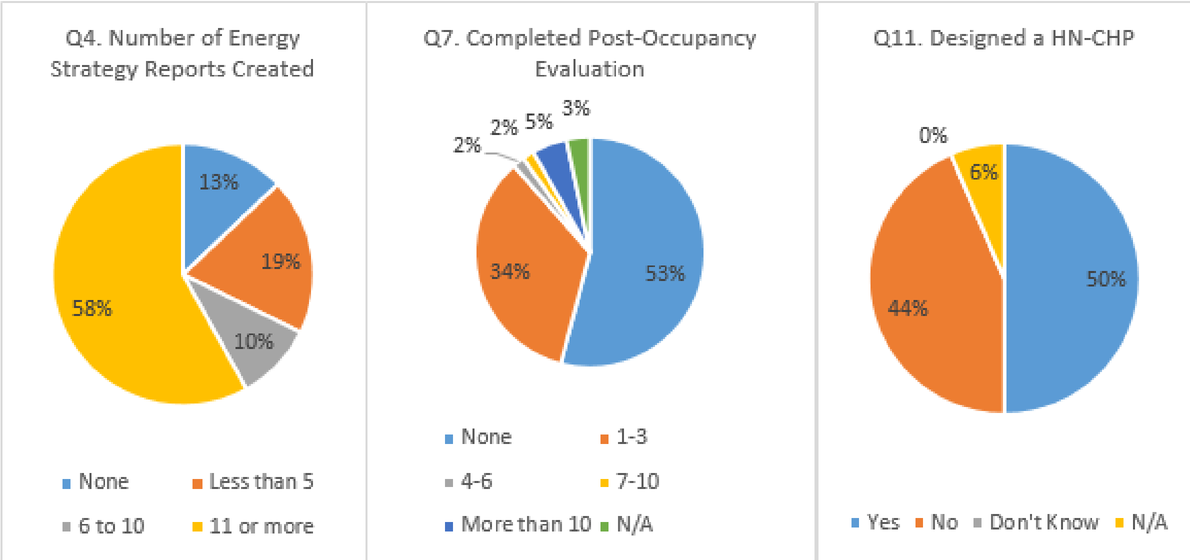


Figure 8.9: Professional Services Experience

The majority of respondents (87%) had experience creating an energy strategy, 8 respondents reported no experience (13%). Experience of creating an ES was not a prerequisite for completing the questionnaire. Over half reported that they had never conducted a POE. This is important finding because a lack of 'feedback' has been identified as one of the causes of the EPG (ZCH, 2013; De Wilde et al, 2014). Half (50%) stated that they had completed the detailed design of a HN-CHP system, while 44% had not. This is important for this research as the PROBE (1999) studies suggested that designs often focused too heavily on LZC features and could lose sight of the overall building performance. Furthermore, complex design has been regarded as one of the causes of the EPG (ZCH, 2013). Therefore, it was important to understand the level of experience and expertise that the respondents had in designing HN-CHP systems.

8.5.3 Opinions Regarding Planning Energy Policy and the Implementation of LZC technologies

This section evaluates the questions that were designed to gather data on the respondent's opinions regarding TLP energy policy, in particular, their opinions on whether the policy targets for CO_2 reduction are being achieved in practice and the different drivers or influences that result in the implementation, and type, of LZC technologies.

The introduction of energy policy as a 'material consideration' of major planning applications has been one of the main instigators for designing lower CO_2 from new buildings. Past reviews suggest planning policy targets are being met routinely by developers (Day et al, 2009). Energy strategy documents are used as an evidence base by planning authorities. Rydin's (2010 p.253) research into TLP found that participants of the EiP believed this type of data to be weak citing that the data does not confirm operational use. Closing ‘the gap’ is seen as vital to ensure that the domestic sector plays its role in achieving the CO_2 emission reduction targets set in UK and EU legislation (De Wilde, 2014; Magalhães & Leal, 2014). Bordass (2004) and De Wilde (2014) also identify that the underperformance of buildings, whether actual or perceived, leads to a ‘credibility gap’. Therefore, it is important to understand the opinions of those professionals who make the early stage decisions designed to lower energy and CO_2 in new developments.

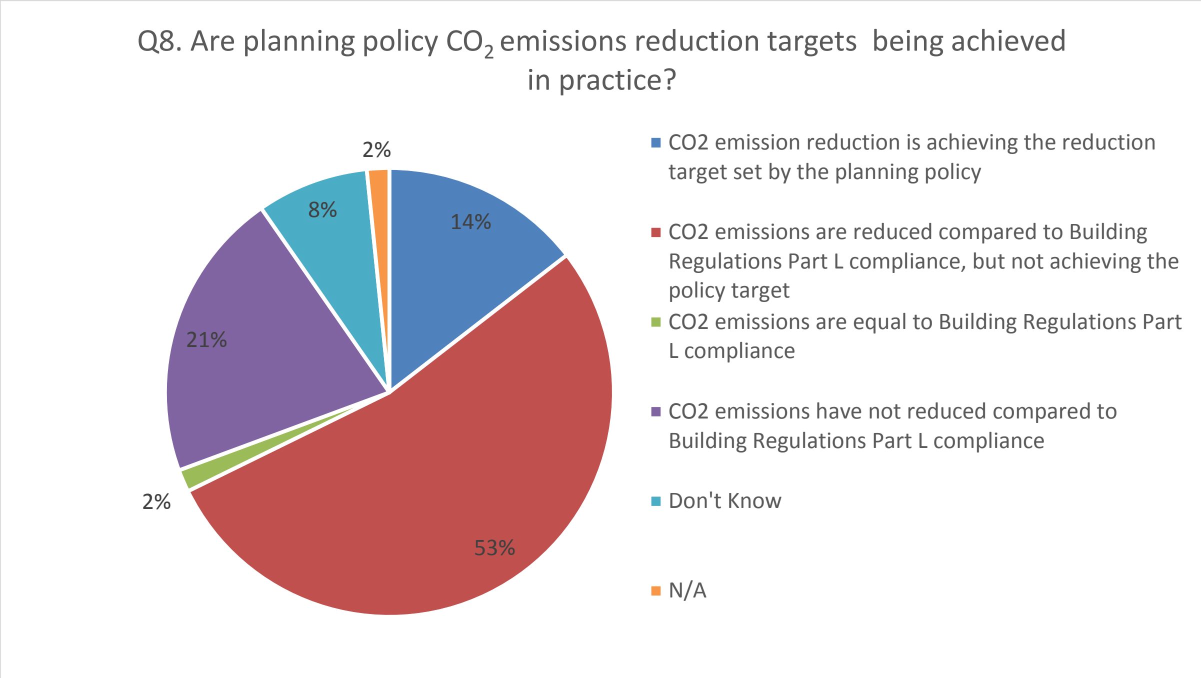


Figure 8.10: Opinions Regarding CO_2 Reduction Compared to Planning Targets

The majority of respondents agree with the statement that CO_2 reductions targets have not been achieved in practice (figure 8.10). Only 14% of respondents are of the opinion that CO_2 reduction targets are being achieved. 21% believe that CO_2 levels have not reduced compared to Part L compliance standards. Over half (53%) are of the opinion that although CO_2 have been reduced below Part L compliance standards, they do not meet the policy target. These findings are significant as they suggest that the majority of professionals making the early stage design decisions do not believe that the targeted CO_2 reductions being presented in the ES will be achieved in practice. This can be described as the ‘credibility gap’ (Bordass, 2004 and De Wilde, 2014), expressed by those that are direclty responsible for the predicted scale of CO_2 reductions and the descisions regarding which type of LZC measures are adopted.

The Mayor's 'energy hierarchy' was created to guide the selection of appropriate measures to achieve the CO_2 reduction targets. The second stage of the energy hierarchy '*be clean'* required designers to evaluate the feasibility of HN and CHP. Between 2007 and 2009 CHP was reported to be the largest contribution to CO_2 reduction in proposed developments (Day et al, 2009). Since 2009, the GLA annual monitoring reports have consistently reported that CHP continued to provide the largest contribution. The findings also demonstrate that the '*be clean'* stage are accountable for approximately two thirds of all predicted CO_2 reductions, this is significantly higher than the other stages of the energy hierarchy (see chapter 2). To understand if this is also the opinion within professional practice, respondents were asked to rank the three stages of the energy hierarchy in the order of which stage they believed saved the most to least CO_2 in practice (figure 8.11).

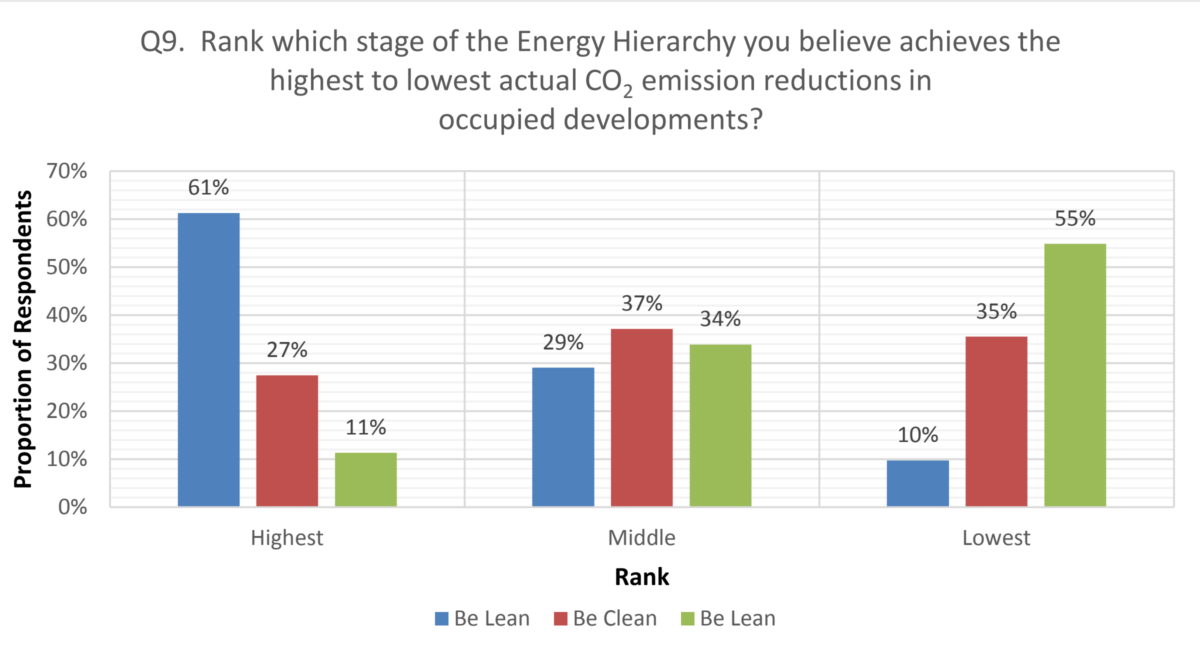


Figure 8.11: Respondents Opinions Regarding the GLA Energy Hierarchy

The '*be clean'* stage (HN-CHP) is not believed to save the highest amount of CO_2 in practice (figure 8.11). The majority (61%) of respondents believe that passive measures (*be lean*) save the highest. Therefore, these opinions are different from the GLA's monitoring study findings. Furthermore, the results suggest that a credibility gap can also relate to specific technologies, in this case HN-CHP. This indicates the potential scale of the EPG associated to new building developments, as HN-CHP is attributed by the GLA to be responsible for two thirds of CO_2 reductions. However, this is not reflected in the opinions of the designers who are responsible for predicting the CO_2 savings.

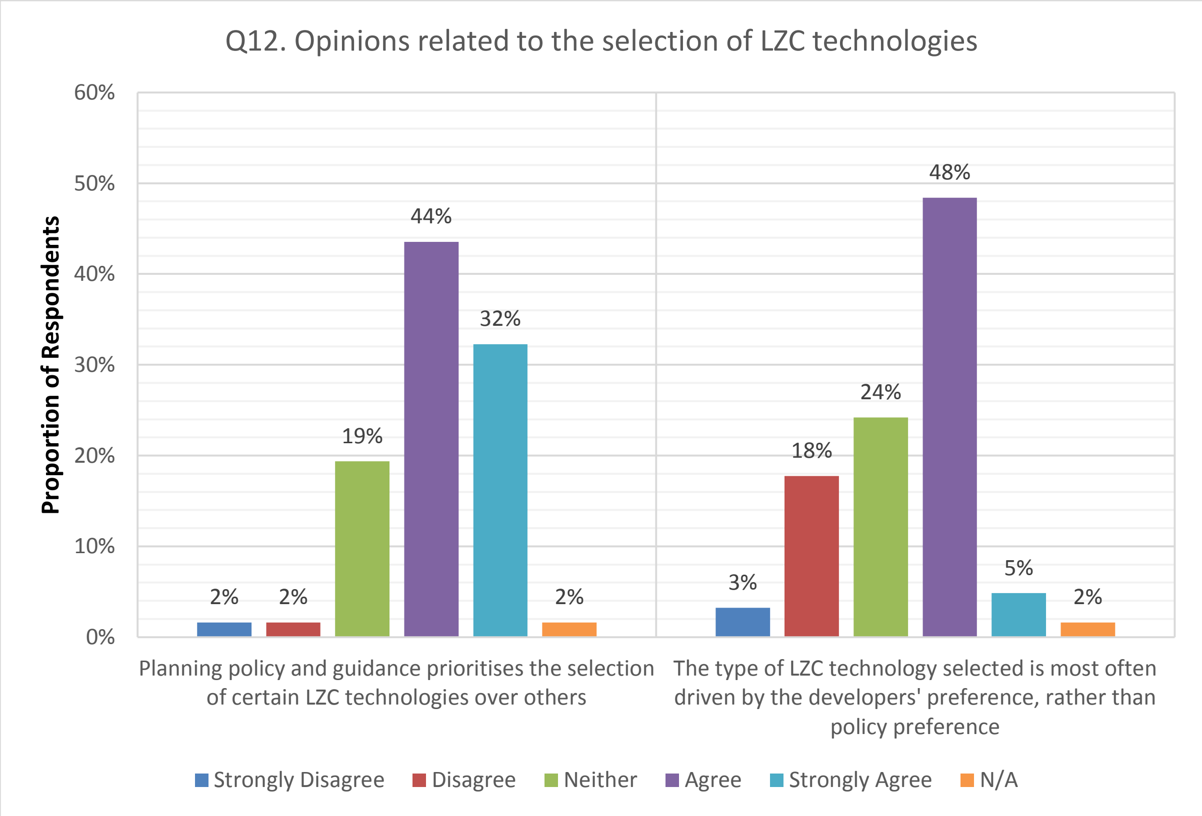


Figure 8.12: Respondents Opinions Regarding the Selection of LZC Technologies

Further questions investigated the respondents' opinions regarding how technological choices are influenced. 76% of respondents either 'agreed' or 'strongly agreed' that planning policy prioritises the selection of certain LZC technologies over others (figure 8.12). 53% of respondents believe that the selection of LZC is most often driven by a developer's preference rather than the policy preference. However, 21% either 'disagreed or 'strongly disagreed'. On reflection, this question could have been constructed to provide more specific opinions on whether compliance with policy has taken precedence over technical or economic assessment, when adopting an LZC technology. Furthermore, a separation of HN-CHP from other LZC technologies in the question would have provided greater clarity of results. This is a potential area for future research.

The GLA policy guidance requires planning officers to secure the commitments made in an ES through planning conditions, rather than seek further feasibility assessment after planning (GLA, 2006a). Furthermore, the GLA claims that the available planning guidance documents provide enough information. Securing the proposals through planning conditions commits developers to install the proposed measures to demonstrate that the building is compliant with the conditions of planning approval. The respondents were asked whether a development's ES requires further feasibility assessment during detailed design stage (figure 8.13).

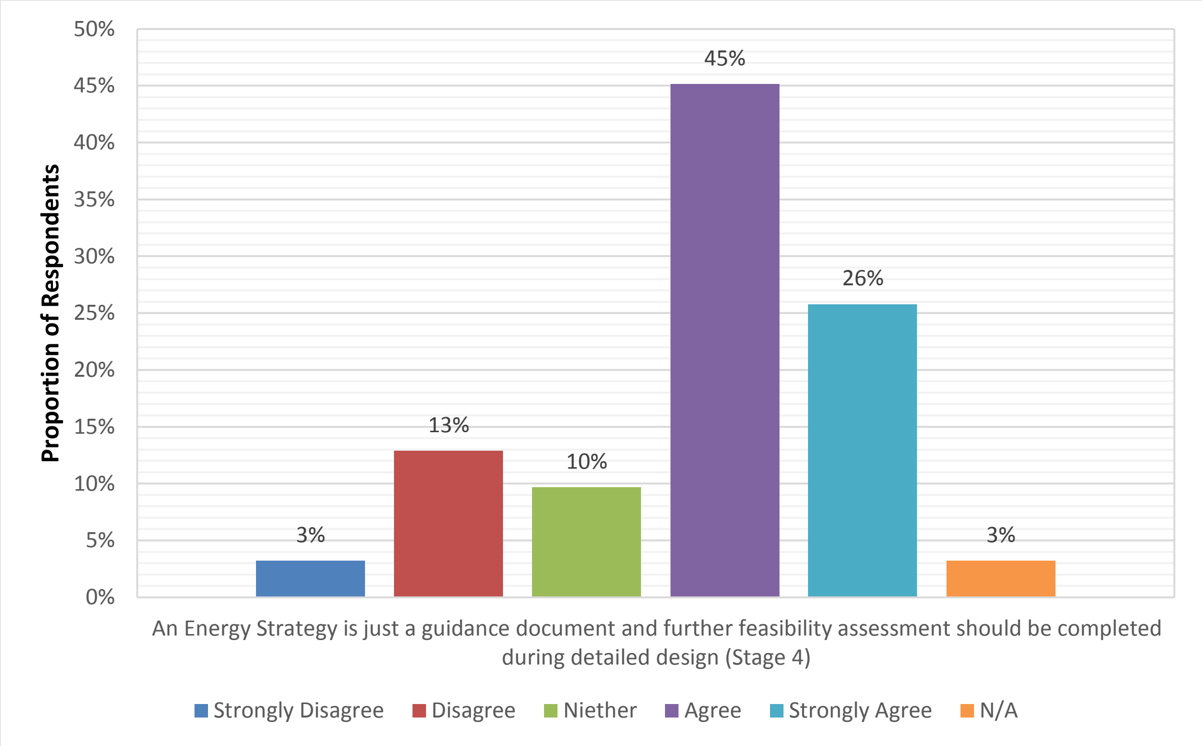


Figure 8.13: Respondents Opinions Regarding the Purpose of an Energy Strategy

Figure 8.13 shows that 71% '*agreed*' or '*strongly agreed*' that the ES is only a 'guidance' document and further feasibility assessment should be completed at a detailed design stage. Only 16% of respondents '*disagreed* or *strongly disagreed*' with this opinion. This result illustrates a clear conflict between GLA and professional practice regarding the purpose of the ES. Analysing these results with the findings of chapter 6, leads to the inference that planning conditions are tying designers and developers into installing LZC technologies that have not had sufficient feasibility assessment.

The respondents were asked to state how frequently aspects of an ES would change during detailed design. This question aimed to understand if the detailed design team and developers do have a level of flexibility to change aspects of the ES post-planning and also to understand the level of influence the ES has on the final design and installation of LZC technology (figure 8.14).

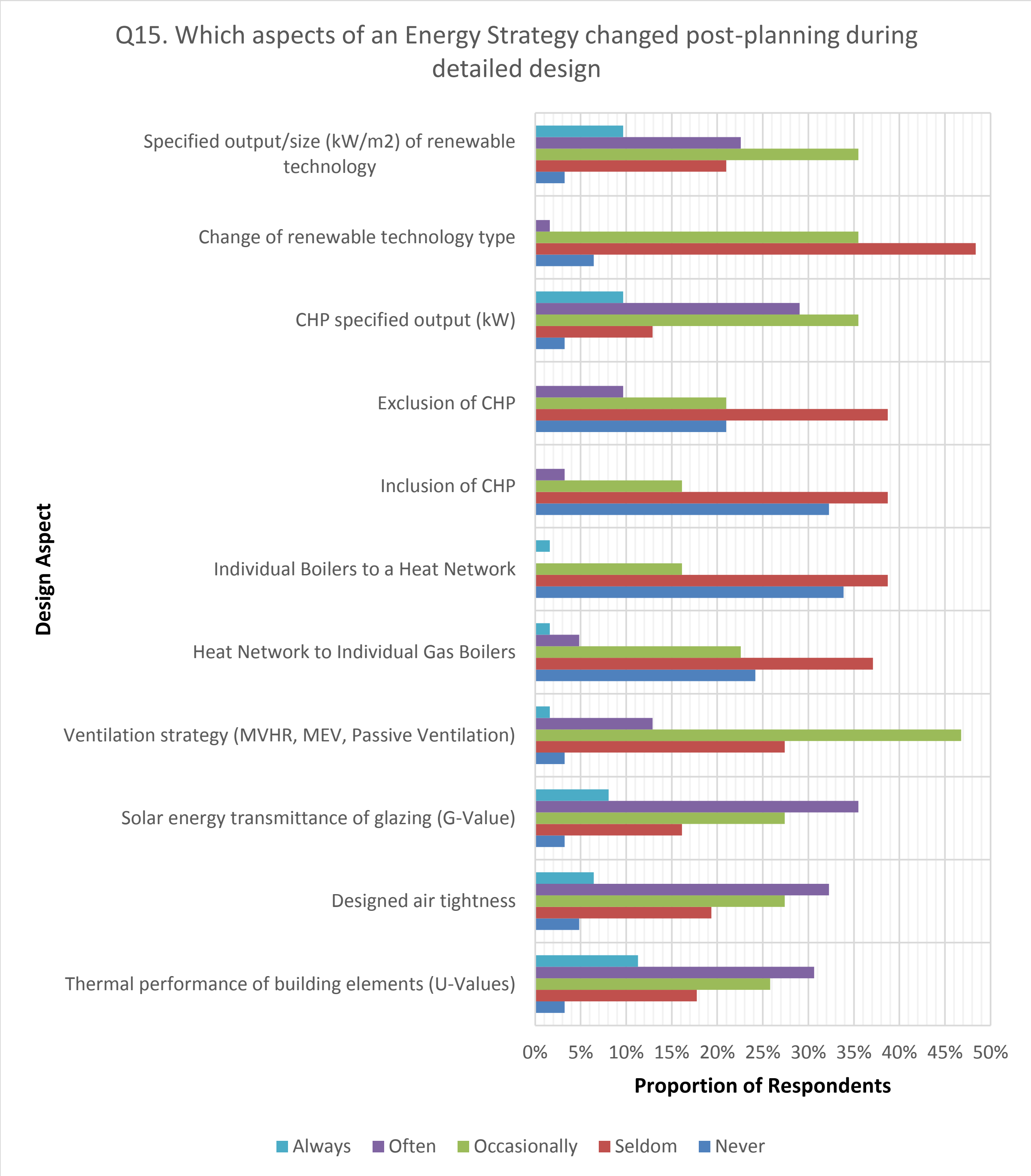


Figure 8.14: Energy Strategy Changes from Planning to Detailed Design

The responses indicated that there is a mixed level of flexibility regarding changes. Passive measures (*be lean* stage) are more likely to change, over other more active measures (*be clean* and *be green* stage). The responses show that measures related to heating systems (energy systems) and RE technologies are less likely to change in detailed design. However, the output or size of the technology might have a level of flexibility but not the type.

These responses demonstrate that the ES has a direct influence on the final technology installed and therefore, emphasize the importance of accurate, detailed and credible feasibility assessment to ensure performance is achievable in practice. Furthermore, the responses illustrate the success of planning policy as a tool for LPA's to secure preferred technology measures.

Finally, the respondents were asked to indicate how often the ES document and the ES designer are involved throughout different stages of a project (figure 8.15 and 8.16 respectively). The Zero Carbon Hub (2013) suggests that developers and planners have a lack of understanding of the impact their early stage decisions can have on design complexity and buildability. Miscommunication and information flow between the different actors (including feedback at the end of a project) is considered a root cause of the EPG (ZCH, 2013; De Wilde et al, 2014). Evaluation and Feedback are described as the most vital part of the planning policy cycle, although they are often not completed (Newton et al, 2005).

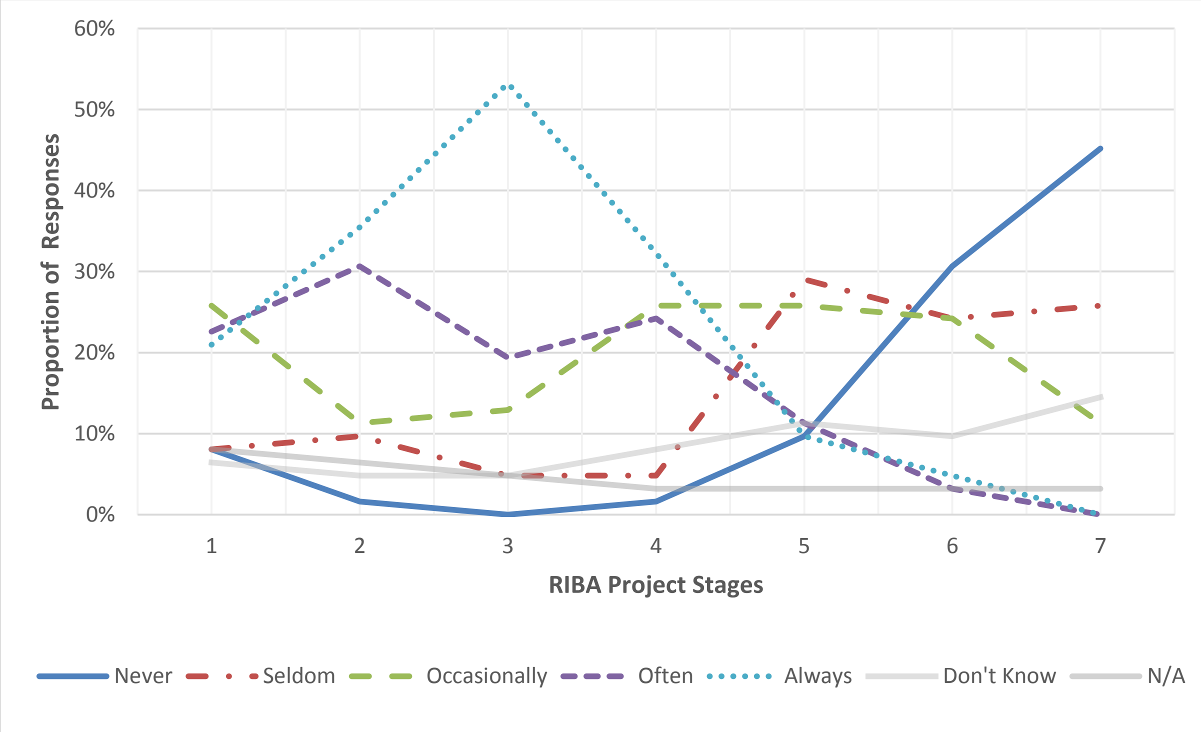


Figure 8.15: The Use of the Energy Strategy document through the different Stages of a Project

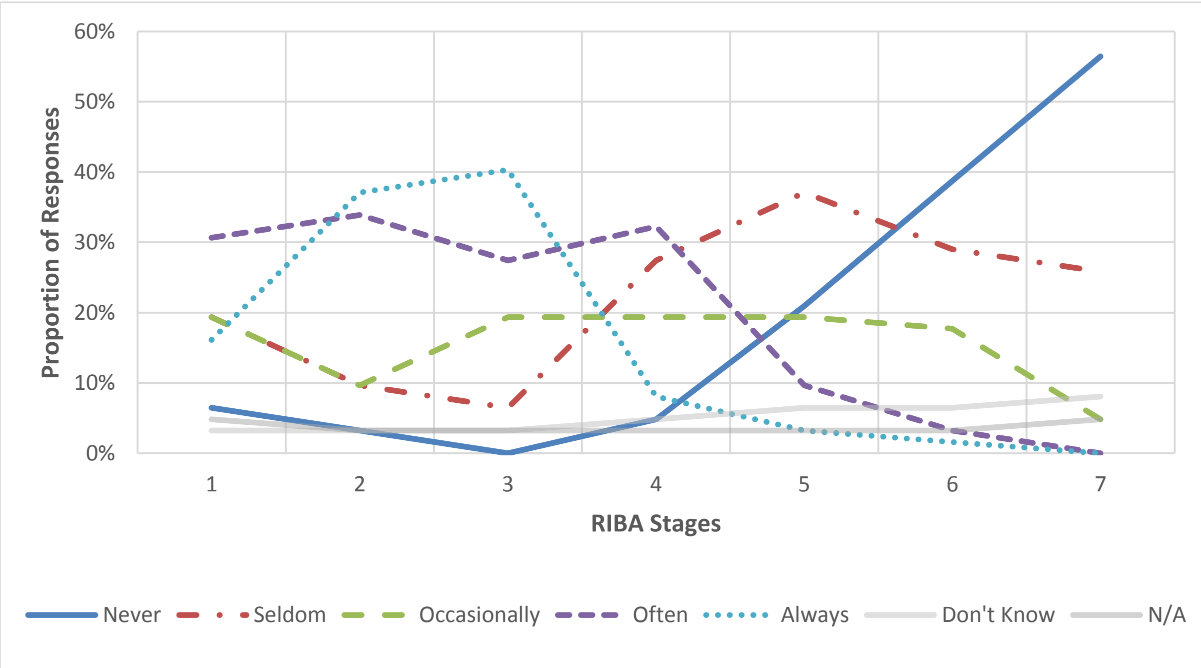


Figure 8.16: The Involvement of the Energy Strategy Designer through the different Stages of a Project

Figure 8.15 suggests that the ES document is likely to have little or no use in a project post stage 4 (detailed design). It also indicates that it is not used when the building is in use (stage 7). The results demonstrate that the ES is unlikely to be used during the installation, commissioning stages or used by the client as part of handover to confirm performance in practice.

Figure 8.16 suggests that the ES designer is unlikely to have involvement in a project post-stage 3 (planning stage). The designer is unlikely to have any involvement during the detailed design, installation, commissioning stages or evaluate the in-use performance. These findings reflect that designers may have a general lack of understanding of the impact of their early stage decisions through the different project stages. Furthermore, important feedback regarding designs that were either successful or underperformed is unlikely to be collected.

8.5.4 Opinions Regarding Feasibility Assessment of HN-CHP

This section evaluates the questions that were designed to gather data regarding the feasibility assessments of HN and CHP and whether planning guidance provides sufficient information to designers on how to conduct the feasibility assessments, and furthermore, to identify the primary source of guidance used by the designers. Finally, it gathers the opinions on what should be included in a feasibility assessment of HN and CHP.

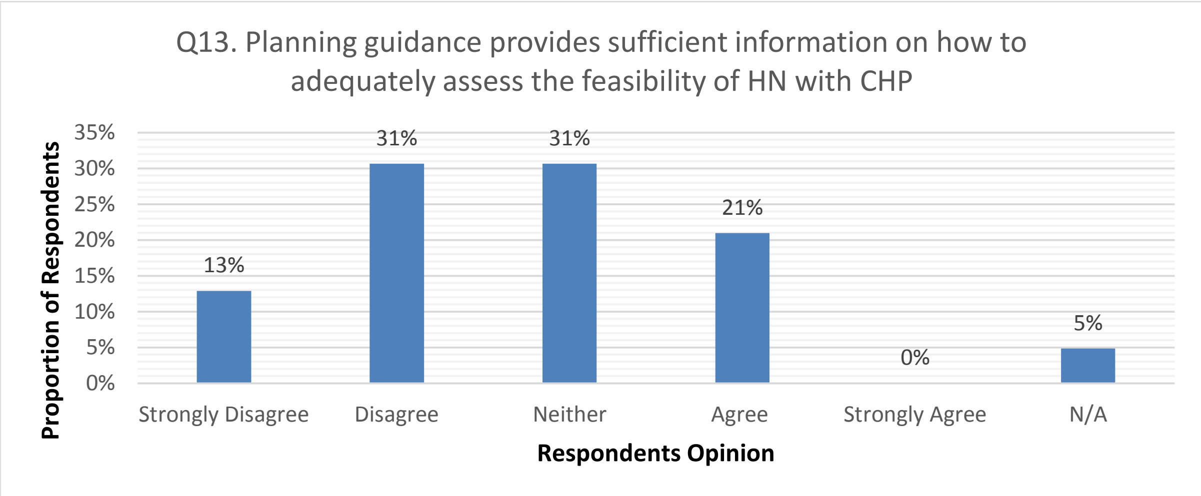


Figure 8.17: Respondent Opinions on the information provided in Planning Documents Related to the Feasibility of HN and CHP

The review of planning policy guidance (chapter 2) identified that designers are required to undertake appropriate feasibility assessment of HN and CHP to comply with planning policy. However, examination of the guidance identified that there was no specific economic or technical methodology prescribed to guide designers on how this should be undertaken. The GLA has provided information and clarification on what it deems as 'appropriate' types of developments to support HN and CHP through successive updates to its guidance. However, no technical or economic methodology is given to date. Figure 8.17 demonstrates that 44% of the respondents 'disagree' or 'strongly disagree' that planning guidance provides sufficient information, although 21% agree that sufficient information is provided.

The examination of ES documents (chapter 6) identified that the key factors prescribed by industry guidance and academic studies are not being routinely used by designers. Therefore, in the absence of a defined method it is currently unknown by what method designers are undertaking technical and economic assessment. The respondents were asked to confirm which document are mostly likely to be used for the feasibility assessment of HN-CHP (figure 8.18).

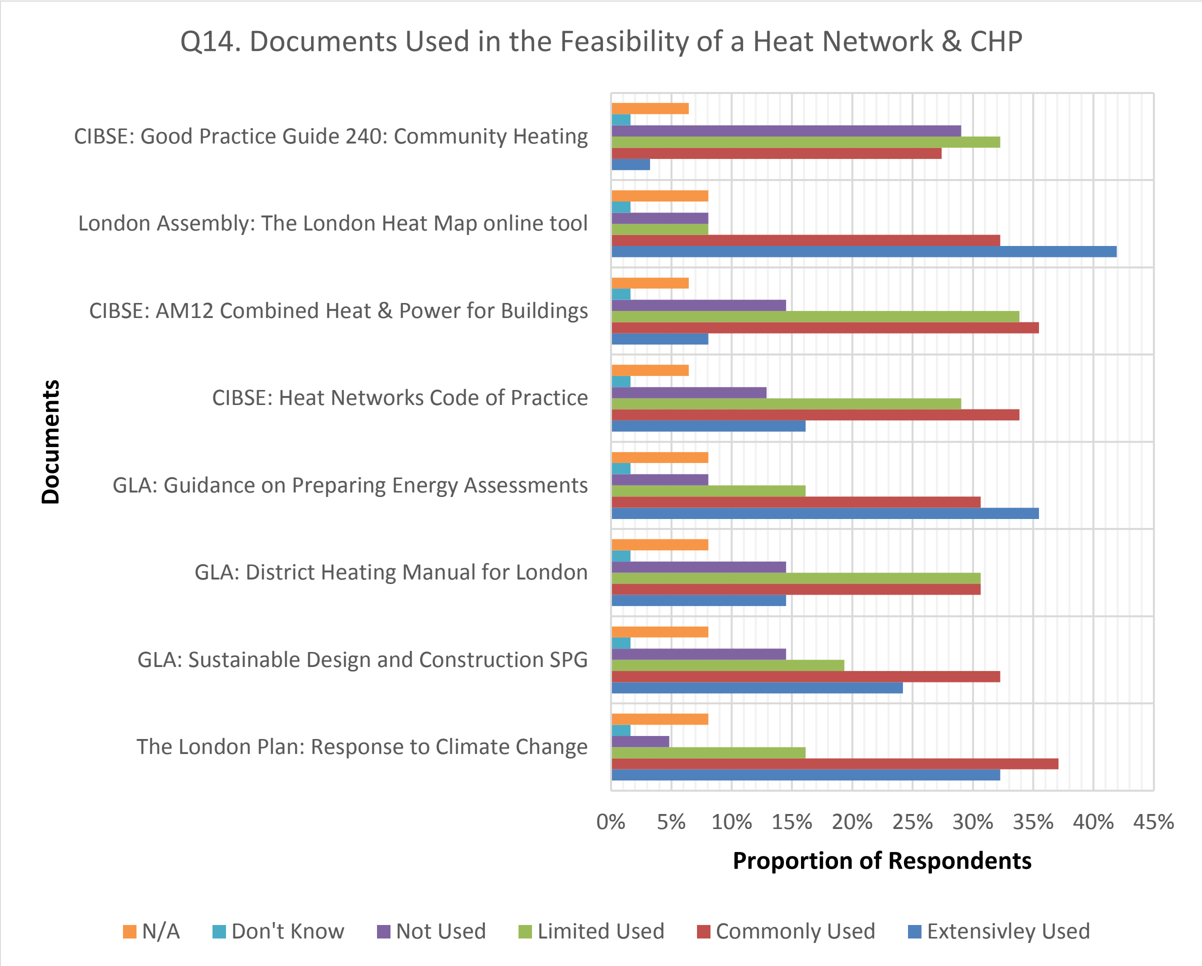


Figure 8.18: The Use of Planning and Industry Documents in the Feasibility Assessment of HN and CHP

Planning guidance documents are more likely to be 'commonly used' or 'extensively used' over industry design documents. Planning guidance documents contain information that defines and describes the planning policy and guidance on how to comply with the planning policy. The four documents (CIBSE Good Practice Guide 240; CIBSE AM12; GLA District Heating Manual; CIBSE COP) that were most likely to have 'limited use' or 'not used' were documents that contain technical information and design guidance. These results suggest that designers are more likely to guided towards policy compliance rather than technical or economic assessment.

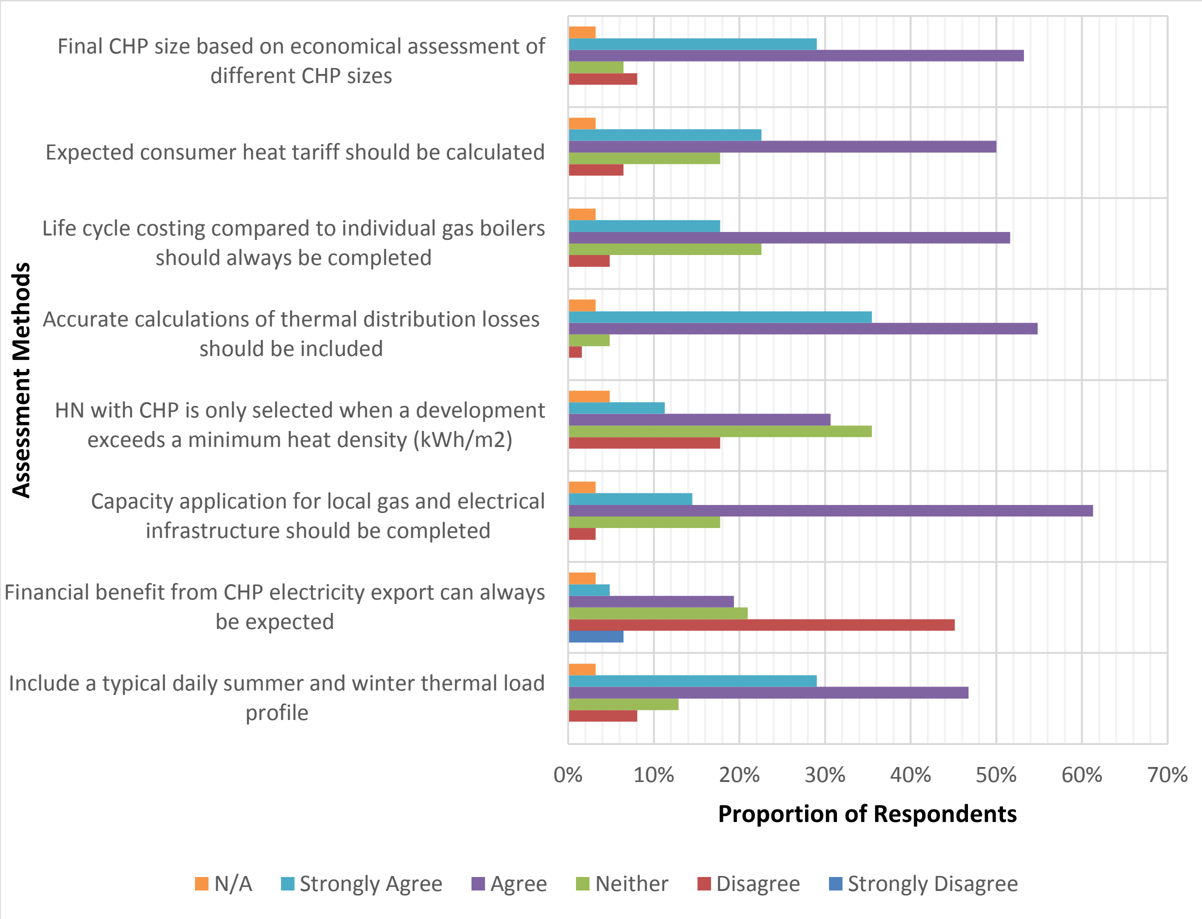


Figure 8.19: Feasibility Assessment Methods for HN with CHP

The ES document analysis found that many of the key assessment factors for HN-CHP system are not being included in ES documents (chapter 6). However, the results of the questionnaire demonstrate that the respondents believe these key factors should form part of the feasibility assessment (figure 8.19). A prominent finding is that 90% of the respondents 'agree' or 'strongly agree' that accurate calculations of thermal distribution losses should be included in the feasibility assessment. Furthermore, 42% agree, compared to 18% who disagree, that a minimum heat density should be exceeded. Results from the document analysis demonstrated that none of the sample ES documents contained an accurate calculation of losses or stated a minimum heat density. The results of the CS analysis (chapter 7) found that DHL was a main cause of the EPG. A similar result is found when comparing the document analysis with the survey results for typical daily summer and winter thermal load profiles. From the survey, 76% of the respondents ‘agree’ or ‘strongly agree’ that typical profiles should be included in the feasibility assessment. However, results from the document analysis demonstrated that 78% did not contain a typical profile of thermal load (section 6.2.2.2).

The high response rates to agreeing or disagreeing with the statements suggest that although these key factors are not explicitly expressed in policy and planning guidance, many of the respondents are of the opinion that they are important to the feasibility of a HN and CHP. Furthermore, the results suggest that the majority of respondents believe that they should be included in the feasibility assessment of HN and CHP. However, these factors are not commonly included in practice (chapter 6).

8.5.5 Opinions Regarding the Energy Performance Gap

As a growing area of academic and industry research, it is important to understand the opinions of those in professional practice regarding the EPG in new developments and HN-CHP systems. The Zero Carbon Hub (2013) suggests that there can be a lack of understanding of the impact that early stage decisions can have on design complexity and buildability of a new development.

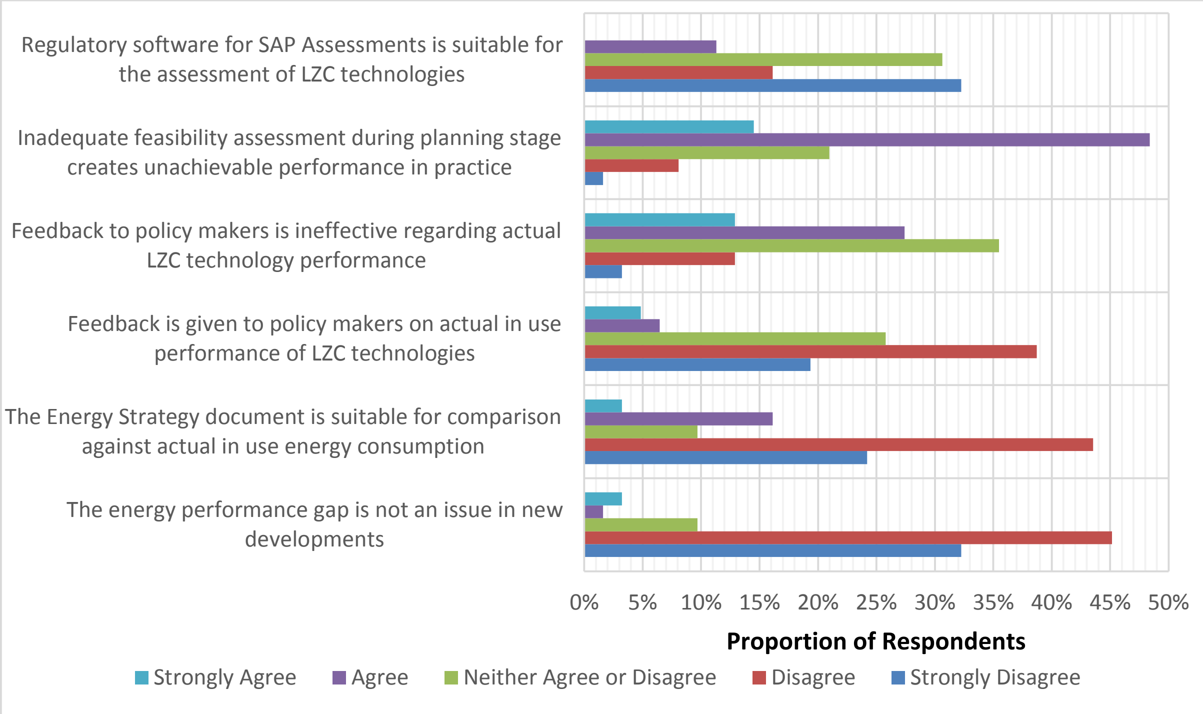


Figure 8.20: Opinions on the Energy Performance Gap in New Developments

The statements put to the respondents related to the energy performance gap, were based on the earlier (chapter 4) examination of existing literature (figure 8.20). The responses showed that 77% of respondents either 'disagreed' or 'strongly disagreed' that the EPG is not an issue in new developments, compared to only 5% who 'agreed' or 'strongly agreed'. Therefore, there is a strongly held opinion that the EPG is an issue in new developments.

The GLA use the ES documents as 'evidence' of policy success in delivering CO_2 reductions from new developments. Day et al (2009) argued that the claims of delivered performance in the ES needs to be assessed once the building is operational. To understand if the ES document can be used as a credible source of predicted performance, the respondents were asked if the document was a suitable for comparison with in-use energy performance. The results showed that 19% 'agreed' or 'strongly agreed'. However, 68% 'disagreed' or 'strongly disagreed'. These results suggest that the designers predicting energy and CO_2 reductions do not believe the ES is suitable to compare against performance in practice. This calls into question the practice by the GLA to present the ES as 'evidence' that policy has been successful in reducing CO_2 and to support more onerous reduction targets. Furthermore, it is unclear how the predictions can be tested once installed and operational, as Day et al (2009) argued, if the documents are not believed to be a suitable as a basis for comparison with in-use performance.

Feedback regarding the evaluation of existing designs is identified as one of the measures required to reduce the EPG (Bordass, 2004; De Wilde, 2014; Menezes et al, 2012). The respondents were asked if they agreed that feedback is provided to planners regarding the in-use performance of LZC technologies. 58% of respondents either 'disagreed' or 'strongly disagreed' that feedback is provided, compared to only 11% who 'agreed' or 'strongly agreed'. The respondents were also asked if they believed feedback to planners is ineffective, 40% 'agreed' or 'strongly agreed'. These findings demonstrate that one of the key identified measures to reduce the EPG is not ordinarily completed in practice. Furthermore, where feedback is given it is seen as ineffective.

When respondents were asked if inadequate feasibility assessment at planning stage creates unachievable performance in practice, 63% of respondents 'agreed' or 'strongly agreed'. Only 10% either 'disagreed' or 'strongly disagreed'. Comparison of these opinions with the earlier findings in this research (chapter 6 and 7), indicates that feasibility assessment undertaken at planning stage is currently inadequate to evaluate achievable performance in practice.

Regulatory energy models, such as SAP, are the method by which energy and CO_2 are calculated for an ES due to their specific expression in the GLA policy and SPG (GLA, 2016). The existing research (chapter 4) has suggested that regulatory tools are not accurate models for the prediction of in-use energy and these are cited as one of the primary causes of the EPG (see De Wilde et al, 2014; Carbon Trust, 2011; Menezes et al, 2012; Van Dronkelaar et al, 2016). The respondents were asked if they agreed that the SAP model is suitable for the assessment of LZC technologies. A small proportion of respondents (11%) 'agree' with this statement, whereas almost half of respondents (48%) 'disagree' or 'strongly disagree'. The results demonstrate that designers tasked with the assessment of LZC do not believe they are using a suitable model to assess the performance of the technologies. However, chapter 6 has demonstrated that the SAP is overwhelmingly the sole model utilised by designers. This suggests that current professional practice is frequently based on policy compliance rather than performance assessment. Furthermore, while SAP remains the prescriptive calculation method there is no incentive for designers to use more suitable methods, especially where doing so would currently undermine a policy compliant ES.

Finally, the respondents were asked for their opinions on the EPG related to HN-CHP, including specific aspects of the system (figure 8.21). This provides important feedback and identifies which specific factors require further attention from designers and researchers in order to reduce the potential of an EPG in HN-CHP systems.

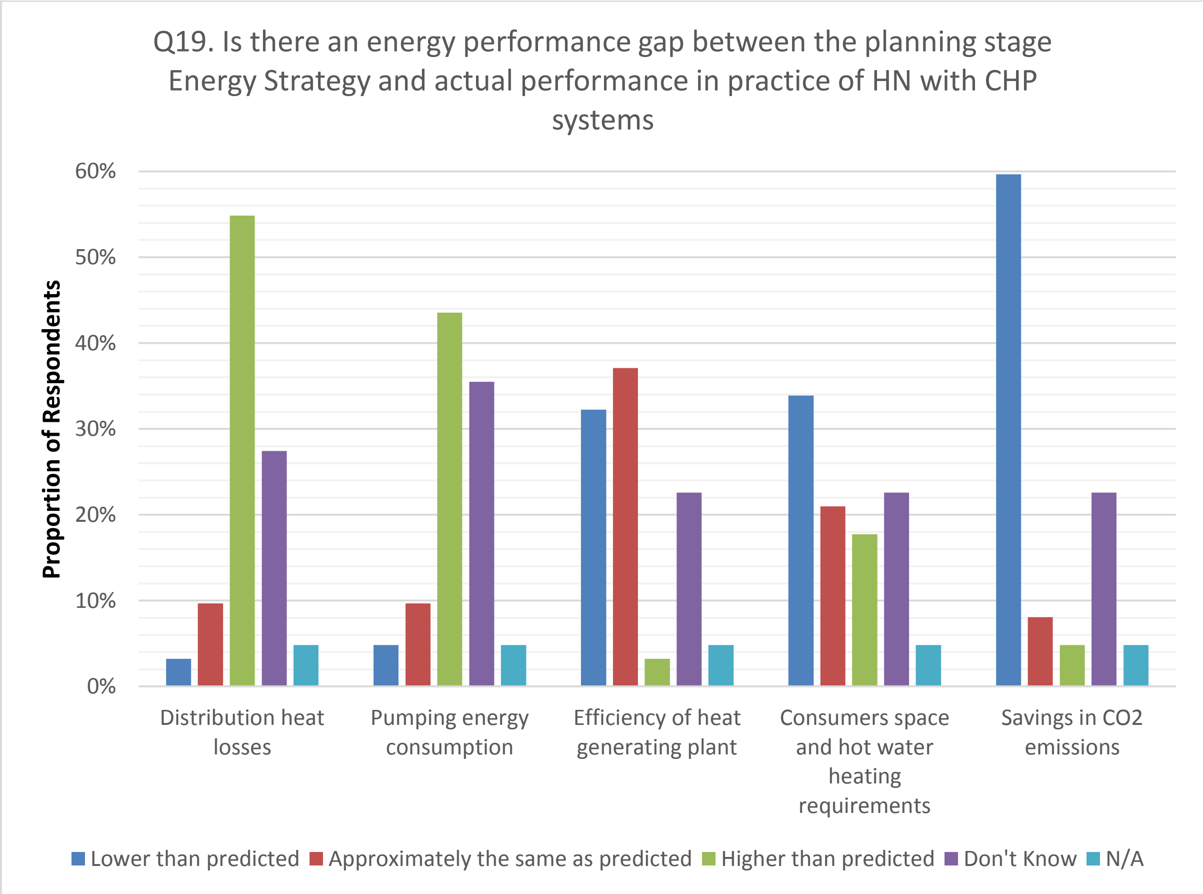


Figure 8.21: Opinions Regarding the Performance in Practice of Heat Network with CHP

Figure 8.21 demonstrates that 60% of respondents believe that less CO_2 is saved from HN-CHP than stated in the ES. Only 8% believe savings are the same as predicted and 5% higher. These opinions identify that those responsible for predicting the level of CO_2 savings, mostly do not believe that they are achieved in practice, contrary to the claimed by the GLA. However, when questioned on the consumer's SH and DHW energy requirements, 34% believe these are lower than predicted. This corresponds to the findings of the CS analysis (chapter 7). This response is also reflective of the earlier opinion that the *'be lean'* stage saves the most CO_2. These findings suggests that in the case of new developments, the EPG is predominantly related to the technology (HN-CHP) rather than energy efficient design (i.e. building thermal performance).

Considering the specific constituents of a HN-CHP system, it was found that the majority of respondents consider DHL and AE to use more energy than predicted, 55% and 44% respectively. Far fewer respondents considered these to consume the same or less than predicted, 13% and 15% respectively. The respondents also appeared to be more confident that heat generating plant (i.e. boilers and CHP) is achieving predicted efficiencies (37%), although a greater number considered efficiencies to be lower (32%) than higher (3%) in practice. These findings reflect the results of the CS POE (chapter 7), that found DHL and AE as predominant causes of the EPG in a HN-CHP system. The CS also found a small reduction in efficiency of the gas boilers compared to assumed performance.

These results have demonstrated that many of the respondents are aware of the EPG that exists in HN-CHP and furthermore, they are aware of the specific aspects of the system that create the EPG. This is perhaps not unexpected given the increasing focus on DHL by recent industry and academic research (BRE, 2016; Blackwell, 2013). What is surprising is that professional practice can be shown to be ignoring or even tolerating the EPG by perpetuating inadequate assessment methods that result in unachievable performance in practice and the absence of effective feedback. This is seen to reflect still Zimmerman & Martin's (2001) (cited by Riley et al, 2009) position that an "*ignorance is bliss mentality exists within the industry*".

8.6 Reflection on Survey Responses

The responses from those in the professional practice have revealed a number of areas that have supported the previously examined research and the findings from the preceding enquiry of this research (chapters 6 and 7). The respondents to the survey are a representative cross section of those professionals that are involved with the creation of ES documents, those that also have experience with the detailed design of HN-CHP, and/or POE.

The responses have illustrated that TLP energy policy has influenced the widespread uptake of LZC technologies. For instance, every LZC technology lay within the range of experience (either extensive or limited) among the respondents. In relation to CHP, all respondents to the survey suggested they had at least some 'limited' experience. The GLA's use of prescriptive policy and guidance such as the *energy hierarchy* and energy systems *order of preference* has influenced designers to prioritise HN-CHP over other technologies. The majority of the survey responses suggested that technologies are most likely to be selected on the basis of developer preferences, and to a less extent policy compliance. It has also been shown how policy can in directly influence the selection of LZC technologies, by stipulating the assessment model (SAP) by which the performance of technologies is assessed. The over optimistic assessment of certain HN-CHP performance in the SAP discourages unbiased practical assessment of the sort, that may lead designers to choose other technologies or solutions. What is thought provoking is that the ES designers appear to knowingly accept the influences directed towards them. The responses showed a clear majority of respondents believe that predicted CO_2 will not be delivered in practice, and more critically for this research, that performance of HN-CHP will be lower than predicted. This is an indication that the industry has accepted a compliance-over-performance approach to low carbon developments.

A low level of knowledge and expertise is seen as one of the obstacles to delivering performance in practice. It can also be seen as an obstacle to identifying and encouraging changes to poor professional practice or policy. The responses have illustrated that there is a reliance on short industry accreditation courses and manufacture-led seminars to disseminate knowledge, with acquisition of formal academic education and professional competency recognition to a lesser extent. This is further reflected in the documentation most commonly utilised for undertaking a feasibility assessment of HN-CHP. The reliance of designers on information and documentation that explain policy, its objectives and most crucially how to comply with it, do not provide a pathway for increased technical expertise or practical knowledge. This occurs at a stage in the project when key decisions are being taken that will have the greatest impact, therefore arguably it is the stage where greatest expertise is required.

The results found that only half of respondents had completed a detailed design of a HN-CHP and approximately only the same proportion had completed a POE. This indicates the lack of experience in relation to delivering design in practice and evaluating the resultant outcomes. The responses further showed that the ES document will have limited use and the designers are likely to have limited involvement post-planning stage and none at all after occupation. This separation from those designing the ES to those tasked with delivering in practice has a parallel with the earlier discussions regarding Rydin's (2010) view of '*deworlding*'. In this segregated process it is not evident at what stage and with whom, the responsibility for performance in practice lies.

The GLA policy places the responsibility for CO_2 reductions with the ES, by securing the commitments through planning conditions. This is also true of professionals involved post-planning, as a LZC technology is unlikely to change post-planning. However, the responses of the survey demonstrated that the designers distance responsibility by proclaiming the ES as 'just guidance' and suggesting that further feasibility assessment should be completed at detailed design stage (stage 4). Furthermore, respondents also suggested that the ES predictions are not suitable for comparison with in-use energy consumption. These findings have identified a conflict in the understanding between the different actors involved in different stages of a project.

One of the most unexpected findings from the document analysis (chapter 6) was the absence of technical and economic feasibility assessment being undertaken, especially in regard to HN and CHP. It was expected that this may be the result of poor knowledge or lack of awareness by the designers. However, the responses have shown that many of the respondents are aware of the key factors relating to feasibility assessment of HN and CHP. The responses also illustrate the predominant opinion that inadequate feasibility assessment in at planning stage will lead to unachievable performance in practice. The implication of these findings is that feasibility assessment, especially related to HN and CHP, undertaken at planning stage is currently recognised as inadequate and will result in unachievable performance in practice. However, the most thought provoking aspect of this implication is that the designers appear to be aware of the inadequacy and resultant unachievable performance in practice. Therefore, until planning authorities define appropriate assessment methods as a prescriptive policy requirement, professional practitioners are unlikely to provide this information voluntarily, especially where doing so would currently undermine a policy compliant ES. These are critical aspects to the understanding of how the planning stage ES is contributing to the EPG.

Feedback through the evaluation of existing designs is identified by industry and academia as one of the measures required to close the EPG. However, the responses have demonstrated that feedback about the in-use performance of LZC technologies is not likely to be provided. Furthermore, where feedback is given to planners it is likely to be ineffective. These responses suggest there is little hope of reducing the EPG as long as feedback is not willingly provided, and perhaps more importantly, not accepted or acted on.

8.7 Chapter Reflection

This chapter has developed and tested a questionnaire to collect data from industry professionals on their opinions and perspectives regarding the adoption of local planning energy policy; methods for assessing LZC technologies; and the EPG in HN-CHP systems. Responses were collected from a representative cross section of those professionals involved with the creation of ES documents and those that also have experience with the detailed design of HN-CHP and POE.

The evidence presented in this chapter has demonstrated that:

- Planning policy and guidance has directly and in directly influenced the choices made by ES designers when selecting types of LZC technologies. Furthermore, designers can be seen to be accepting the influences directed towards them, conducting a compliance-over-performance approach to low carbon developments.
- It has been identified that there is a loss of technical contact between the ES designers and those who deliver and operate the technology within the real world context.
- The ES designers typically rely on disseminated knowledge from planning authorities and building regulations, which limits the development of their technical expertise and practical knowledge.
- The findings have identified a conflict in the understanding between actors regarding the purpose of ES and where the responsibility for performance in practice lies.
- Those in professional practice have been shown to be aware that current HN-CHP feasibility assessment is inadequate and that this will result in unachievable performance in practice.
- Respondents identified DHL and AE as aspects of a HN-CHP system that are likely to consume more energy than predicted.
- These findings suggest performance feedback is often not provided and when provided it is ineffective. An ‘ignorance is bliss’ mentality is considered to be prevalent in the implementation of planning energy policy.

The implication of the findings presented in this chapter is that the designers are aware that the feasibility assessment of a HN and CHP undertaken at planning stage is currently inadequate and will result in unachievable performance in practice. Furthermore, the conduct in professional practice of compliance-over-performance is unlikely to result in information being voluntarily presented, especially where doing so would currently undermine a policy-compliant ES.

CHAPTER 9: SUMMARY OF FINDINGS, CONCLUSIONS AND LIMITATIONS

This chapter presents the findings of the evidence that has been collected through chapters 6 to 8. The findings are used to examine the secondary research questions set out in chapter 5. Conclusions drawn from the research, identifies the limitation of the research and offers suggestions for future research areas. Additionally, the wider implications of the research for the academic field and stakeholder groups within the construction industry is discussed.

9.1 Research Findings

The primary research question defined the direction of the research, with secondary questions posed to elaborate the focus of the enquiry within the research theme. This section presents the findings from the evidence collected to answer the secondary research questions. The findings use the evidence collected from all research methods employed in this research and a method of triangulation is used to corroborate findings. Triangulation is used to remove the potential of biases from the evidence collected or by the investigator's own biases (Bowen, 2009).

9.1.1 How do local energy policies influence the selection of low and zero carbon technologies?

The analysis of the existing primary and secondary research examining TLP identified that policy has a direct influence on the type of technology selected by designers. This was observed in the changing trends in technology capacity directly succeeding policy changes. This was most notably witnessed in the prioritisation of CHP in the energy hierarchy that resulted in a significant increase in reported CO_2 savings and a corresponding decline in savings from other technologies (chapter 2). All of the sampled energy strategy documents analysed followed the hierarchy as the chronological method by which technologies were assessed (chapter 6). The analysis identified that the prioritisation of HN-CHP resulted in other technologies being assessed on the basis of compatibility with HN-CHP, rather than on their merit to reduce CO_2 in their individual context; thereby, reducing the level of overall technical feasibility assessment being undertaken (chapter 6). This was further corroborated by the survey findings where, it was identified that respondents perceive the prioritisation of a technology in policy as an influence on the choice of technology adopted (chapter 8).

The research also found that the GLA policy can have an indirect influence on the selection of HN-CHP systems, through the adoption of the SAP methodology as the means of evaluating compliance with policy targets. The prescriptive approach of the GLA policy has transformed the SAP assessment from a regulatory compliance tool to a de facto design tool (chapter 4). The analysis of energy strategy documents found that the SAP is almost the only tool adopted by designers for evaluating LZC technologies (chapter 6). At the same time in corroboration with the existing academic research examined (chapter 4), the case study analysis found that the SAP is an inadequate method for evaluating the performance of HN-CHP. The over-optimistic assessment of performance discourages unbiased practical assessment methods that could otherwise lead designers to choose other technological solutions (chapter 7). This indirect influence of policy is corroborated by the survey findings that the majority of respondents do not perceive the SAP as a suitable method for assessing LZC technology feasibility, and that the overall CO_2 savings predicted are lower in practice than the policy intent (chapter 8).

9.1.2 What are the motives for the adoption of a Heat Network and CHP in a new residential development?

The content analysis of ES documents presented found that several themes emerged as motives to adopt HN and CHP. Conversely the same themes were also found to be motives to discount them. *Density* was found to be the most prominent theme followed by *economic, CO_2 reduction*, *efficiency*, *planning policy* and *future proofing* (chapter 6). The low frequency that these themes appeared across the entire sample demonstrated that no one theme was considered universally essential to the adequate assessment of HN or CHP. This was contrary to the examination of the existing research literature, policy guidance, and industry technical guides, which identified several of the themes (*density, efficiency, CO_2 reduction, economic*) as critical to the evaluation of HN and CHP (chapter 2 and 3). This was corroborated by the findings of the post occupancy evaluation, which found corresponding themes were associated with the achievable performance in practice (chapter 7).

It was identified that the primary causes of the EPG corresponded to two particular themes, distribution heat loss and auxiliary energy (chapter 7). These themes were given minimal consideration in the sampled energy strategy documents (chapter 6), which suggests that there is a potential lack of awareness within professional practice regarding the impact of these factors on the feasibility of a HN-CHP system. This would support the Zero Carbon Hub

(2013) suggestion that there is a general lack of understanding regarding the impact early stage decisions can have on design. At the same time the survey data demonstrated that the majority of respondents agreed that these themes should form part of the feasibility assessment of HN-CHP and that these aspects of the system were unlikely to meet the intended level of performance in practice (chapter 8). Therefore, it has been found that while professional practice may already have an appropriate level of awareness, it is not routinely being acted on in practice to influence decisions.

The substantive finding of the content analysis of the energy strategies was that themes were most often presented as notional concepts, rather than robust technical reasoning. The concepts were found to be devoid of technical discussion or quantitative value that would provide unequivocal justification of the designer's judgment and decisions. The research identified that without this the developments lacked individual context and the result was a decontextualised notional motive for the adoption of a technology (chapter 6). The post occupancy evaluation demonstrated that notional motives, such as *density,* CO_2 *reduction*, *efficiency*, can be invalidated under technical interrogation (chapter 7).

The absence of robust technical data or discussion presented in the energy strategies was primarily associated with the types of documents most often utilised by the designers, and their level of formal training. The survey found that policy documents were far more likely to be referenced than industry technical guidance (chapter 8). The examination of the policy documents identified an absence of prescriptive methodology for the technical or economic assessment (Chapter 2). The survey findings also identified that the majority of respondents had qualifications linked to regulation compliance rather than formal technological or engineering qualifications (chapter 8). These findings were linked to the content analysis that identified that a proportion of respondents expressed policy compliance as justification of technology selection (chapter 6). The findings drawn from this evidence is that policy compliance, as a justifiable motive for the adoption of HN-CHP, is of equivalency to technical or economic assessment.

The research further identified that a HN and CHP are unlikely to be excluded from the final installation if planning approval has been granted (chapter 2 and 8). Consequently, the accuracy and reliability of the assessment methodology and the professional opinions that underpin the designer's motives are paramount to the deliverable performance in practice.

There are wider complexities of project delivery, for example: financial, programme, planning complexities, political influence, etc. that could influence the decision to adopt HN-CHP. These wider complexities are outside the boundary of this research, but present an opportunity for future research to elaborate on and collaborate with existing research in these areas.

9.1.3 Do local energy policies promote appropriate feasibility assessment of Heat Networks and CHP?

The presented examination of the planning guidance found that the GLA suggest that there is sufficient information available through published planning guidance for the economic and technical assessment of proposed measures. However, examination of the policy guidance identified that there was no prescriptive method presented for either technical or economic assessment of HN and CHP. The evaluation of the documents did identify that information is increasing in more recent publications. However, this was found to be scenario based descriptions rather than structured methodology or quantitative values (chapter 2). Evaluating these findings with the academic and industry technical guidance (chapter 3), it was found that the current published planning documents provide insufficient guidance for the appropriate assessment of HN and CHP. This is corroborated by the content analysis that found an absence of technical or economic evaluation (chapter 6) and furthermore with the survey data, which identified that the majority of respondents do not believe that sufficient information is given in planning guidance (chapter 8).

The content analysis completed in this research found an absence of technological or economically focused feasibility assessment of HN and CHP. The information presented by the designers comprised predominantly notional concepts of various technical or economic themes (chapter 6). The analysis also identified that many of the themes presented were inconsistent with the contextual aspects of the building development and the scenario based descriptions presented by the GLA (chapter 6). The use of notional themes was found to be a proxy justification for the selection of a technology to suit the most dominant motives, whether planning policy or developers preferences. This is considered to be a continuation of the 'success storyline' described by Rydin (2010) (chapter 2), that the installation of an LZC technology will, by definition, result in energy and CO_2 reductions. Such storylines, in the context of this research, result in a barrier to any meaningful technological or economical assessment.

The case study presented in this research tested the professional opinions underlying the designers' presented motives for selecting a HN-CHP. The findings demonstrated that these underlying perspective could be invalidated by technical interrogation. Furthermore, the energy performance indicators derived from existing research and industry design guides, have been found to present a more accurate expectation of performance in practice than the energy strategy design intent, in turn, reducing the scale of the observable energy performance gap (chapter 7). The survey results also found that:

- A majority of respondents agreed that current planning guidance does not provide appropriate assessment guidance;
- CO_2 reduction targets were not being achieved in practice; and
- Inadequate feasibility assessment creates unachievable performance in practice (chapter 8).

These findings identify that the current feasibility assessment of HN and CHP undertaken in the context of planning policy compliance are inappropriate to provide a reasonable design expectation of performance in practice.

The findings of this research have demonstrated that the current feasibility assessment methods are inadequate, despite the availability of academic and industry guidance that has been shown to be a more effective (chapter 7). The research concludes that the prescriptive nature of the London Plan policy, most prominently defined by the *energy hierarchy*, *energy systems order of preference* and the over-optimistic evaluation methodology discourages, rather than promotes, appropriate feasibility assessment of HN and CHP.

The research findings suggest that so long as feedback to planners is perceived as rare or ineffective (chapter 8) and the energy strategy documents are upheld as evidence-based policy (chapter 2), it is unlikely that policy will change to promote more appropriate feasibility assessment methods. Furthermore, professional practice is unlikely to instigate changes voluntarily, especially where doing so would undermine a policy compliant energy strategy.

9.1.4 What scale of energy performance gap can be found in a small residential HN-CHP system?

This research presented a post occupancy evaluation of a HN-CHP system serving a residential building. The novel approach of this research was to evaluate the professional opinions that justified the selection of HN-CHP, as well as the quantitative savings (energy and CO_2) anticipated in the planning stage energy strategy and the design regulatory assessment. A further unique aspect was to evaluate the observed performance against energy performance indicators. The purpose being to understand the prominent causes of the observable energy performance gap, and if the adoption of appropriate assessment methods could provide a more realistic evaluation of in use performance.

To determine an independent evaluation of the overall energy performance gap, the primary energy factor was calculated. The examination of design intent (PEF@1.32) and the observed performance in practice (PEF@3.00), showed that there was a significant performance gap (chapter 7). Although, not as high as observed in some non-domestic building research (chapter 4), this still represents a significant difference from the intended energy consumption and savings of CO_2 presented in the energy strategy and design regulatory assessment. It has therefore been found that the design intent, including planning commitments of energy and CO_2 reduction, was not delivered in practice.

Werner (2006), identified the need to evaluate integral factors of the system to identify inefficiencies that could be hidden by the integration of high efficiency technologies. The results of the analysis found that the overall performance can be significantly impacted by the performance of the individual factors and not all were equally relative to the overall performance. It was found that the distribution heat loss and auxiliary energy were the two most prominent factors influencing the scale of the performance gap observed (chapter 7). These findings are consistent with other examined industry studies (chapter 4). The importance of these two factors was also observed within the survey data. From those surveyed, the majority expected these two factors to result in higher energy than predicted (chapter 8). The survey findings suggested that there could be an existing understanding within professional practice of the relationship between these two factors and the scale of energy performance gap. It is therefore surprising that the content analysis of energy strategy documents found little consideration of these factors as part of the planning stage assessment (chapter 6).

To understand how the adoption of detailed assessment methods at early stage may influence the scale of the performance gap, the values for distribution loss factor (a measure of DHL) and auxiliary energy were corrected following assessment methods derived from academic research and industry guidance. The revised primary energy factor for the corrected values was found to be a considerable improvement (PEF@2.07), although the gap was still significant. This research therefore found that a proportion of the performance gap was created by the assessment method adopted that did not reflect deliverable performance in practice. These findings were corroborated by the results of the survey, where a large majority of respondents identify poor feasibility assessment as creating unachievable performance expectations in practice and that the accurate calculation of distribution heat losses should form part of an energy strategy feasibility assessment. Furthermore, a majority of respondents disagree that the SAP (the GLA prescribed assessment methodology) is suitable for the assessment of LZC technologies. These findings suggest that professional practice has the opportunity to reduce the energy performance gap created at the planning stage by adopting known appropriate assessment methods as part of the energy strategy.

The domestic thermal demand in the post occupancy evaluation was found to be lower than the design expectation, which corroborates similar research (for example Monahan, 2013). Therefore, it can be argued that the industry response to the low energy design element of the London Plan policy (*be lean*), is unequivocally leading to a reduction in domestic thermal energy demand (chapter 4 and 7). This is supported by the evidence of a majority of those surveyed, who rank the *be lean* stage as achieving the highest CO_2 reductions in practice (chapter 8). However, these findings and other corroborative research studies, are in direct contradiction of the GLA published evidence, that suggests the overwhelming majority of CO_2 reductions are a result of the *'be clean'* stage (chapter 2), not from LZC technologies. Therefore, any meaningful effort by government or the house building industry to reduce the scale of the energy performance gap must start with impartial, evidence-based technological assessment procedures.

This research has found potentially wider implications for the GLA policy aspirations to integrate smaller heat networks into a low carbon decentralised energy network, which was found as a predominant justification for the adoption of a heat network (chapter 2, 3 and 6). However, unless, as found in this research, the true energy consumption of the heat network is understood, calculated and evaluated, the ability of a future low carbon, zero carbon or secondary heat technologies to deliver anticipated energy and CO_2 reductions in practice is significantly undermined.

9.2 Research Conclusions

9.2.1 Introduction

The aim of this research project was to evaluate if the local energy policies that promote the adoption and implementation of HN-CHP technologies in small scale residential buildings are leading to the anticipated reductions in CO_2 emissions. This was investigated to expand academic research in the field of building energy performance and to inform policy makers of the success of polies to deliver real world CO_2 emission reductions.

To ensure that this strategic aim of the project was met, several objectives were defined to enable the research to be focused around the key themes of:

- Understanding current professional practice related to the creation of an energy strategy for a new development including: the methods of feasibility assessment, evaluation of potential energy and CO_2 savings, and the motives that inform designers' decision to select a HN-CHP system.
- Understanding how planning policy and guidance influences the selection of LZC technologies, including HN-CHP.
- Establishing whether an energy performance gap exists between design intent and performance in practice of a HN-CHP, and if so, what is the scale and cause of the gap.

A detailed analysis of the research problem, available research methods and justification of their adoption was presented in chapter 5. A primary research question was formulated:

> *Are the local energy policies that promote the adoption and implementation of Heat Networks and CHP technologies in small scale residential buildings leading to the anticipated reductions in energy and CO_2 emissions and, if not, what are the reasons?*

The prescribed research methods were implemented through chapters 6 to 8, to ensure that the collection of data and findings drawn would have the appropriate rigour and validity. Chapter 9 presented the findings from the evidence collected to answer the secondary research questions. Conclusions drawn from these research findings are now presented to answer the primary research question.

9.2.2 Conclusions

In the house building sector the UK Government has introduced national strategies and legislation that have directed local planning policy to reduce energy consumption and the resulting CO_2 emissions in new building developments. This has resulted in a new facet of the planning appraisal process, in which the assessment of energy, CO_2 emissions and technology has now become a material consideration of planning approval.

The GLA, through its strategic plan for London, has included planning policy that requires developers to adopt a range of energy efficiency and LZC technological measures to reduce CO_2 emissions significantly beyond the building regulations baseline. Developers are required to submit an energy strategy document to demonstrate how the design proposals have implemented the planning guidance and how the chosen measures achieve the policy targets. The commitments made in the energy strategy document are secured by planning officers through planning conditions to ensure measures are implemented during construction. The GLA also uses the energy strategy documents as evidence to evaluate the outcomes of the policy, identifying the number of compliant schemes, the increased capacity of technologies and the overall committed reductions in CO_2 emissions. The results directs future policy decisions and support revisions to the London Plan through the evaluation in public. The GLA results claim lower CO_2 emissions and support the development of prescriptive policy that drives the selection of perceived successful technologies. However, despite calls from academia and the house building industry, the GLA does not include the evaluation and feedback from operational performance, such as the actual CO_2 emissions reductions delivered in practice, if any. Feedback to planners regarding in-use performance is low. Meanwhile, many of the energy strategy designers have been found to have little or no project experience of the detailed design, installation or the evaluation of the measures they are proposing. This is identified as limiting the opportunity and ability to gain and transfer feedback, which existing research has identified as a critical element of closing the energy performance gap. The GLA's use of energy strategy documents as a basis for policy evaluation rather than empirical data, underpins an implicit expectation by policy makers that the implementation of energy efficiency and LZC technologies will, by definition, result in CO_2 emissions reductions in practice.

The prescriptive type of policy implemented by the GLA (e.g. energy hierarchy and energy systems order of preference), has been demonstrated to influence the specific type of technology being selected by designers. Heat networks and CHP have been the central technological focus of the GLA for many years, being heavily prioritised in policy. The success of the London Plan to increase the uptake of these technologies is unequivocal, with two thirds of the committed CO_2 emission reductions attributed to these technologies. Their performance in practice is therefore fundamental to the level of CO_2 emissions reductions actually achieved and ultimately the success of the GLA policy. Despite the widespread uptake, particularly in small scale developments, there are few academic studies providing empirical data of actual performance in practice.

The potential benefits of heat networks and CHP are evident in the number of academic studies and industry publications dedicated to optimizing efficiency, CO_2 emission reductions and economic payback. The literature also emphasises the technological and economical complexity of these technologies and the rigorous assessment that must be applied to determine viability. The vast majority of the research and design guidance (including the GLA supplementary planning guidance) identifies these technologies as being appropriate for large mixed-use developments with a high constant thermal demand. However, the GLA monitoring studies demonstrate that these technologies are being adopted regularly in small scale residential developments. Meanwhile, the industry's response to low energy design is leading to a significant reduction in domestic thermal energy demand. Therefore, heat networks with CHP are being implemented in a new environmental context, contrary to their traditional technological traits. Rigorous and reliable feasibility assessment is arguably even more essential to determine the expected performance specific to each development's unique context. However, the evidence presented has demonstrated that the prescriptive nature of policy and the over-optimistic evaluations of the prescribed assessment methodology, discourages rather than promotes appropriate feasibility assessment. Furthermore, the professional expertise and formal training of the energy strategy designers is predominantly related to legislative compliance. Their type of training does not consider the engineering and scientific principles of the technological solutions. The evidence has shown that the energy strategy assessments being undertaken at the planning stage are currently inadequate to represent deliverable performance in practice from a heat network with CHP. Consequently, this will inevitably result in an energy performance gap.

The energy performance gap is not wholly created in the action or inaction at a single point in a project or by a single decision. The accumulation of the total gap is observable at almost every stage of the project process. The assessment of energy performance is a complex and intensely investigated aspect of the energy performance gap. One of the prominent considerations of this area is the uncertainties or unknowns within the assessment. The contrary phenomenon identified in this research, is that many energy strategy designers acknowledge the inadequacy of the planning stage assessment and are aware that it will not lead to the intended CO_2 emission reductions in practice. Existing more technical assessment methods and information provided by industry, and academic research, have been shown to provide a more appropriate evaluation of deliverable performance in practice, although these methods are rarely, if ever, adopted at planning stage. So long as professional practice remains complicit in the adoption of prescriptive policy and inadequate assessment methods, the opportunity to reduce an early stage contribution to the energy performance gap is missed.

The success of local planning policy, such as the London Plan, to drive developers towards the adoption of LZC technologies is an unequivocal success. The contrast is that the delivered outcomes of CO_2 emissions reductions may not be as intended. Prescriptive policy can lead to an implicit expectation of outcome, which in turn discourages the appropriate consideration of the complex technological, economic and contextual environment of each development. Therefore, until policy makers promote adequate feasibility assessment as an integral part of policy, the current conduct in professional practice of compliance-over-performance is unlikely to change. Consequently, the planning policy that promotes the adoption and of implementation of heat networks and CHP systems will be highly unlikely to achieve the intended CO_2 reductions in practice. In some instances it may lead to the unintended consequence of increased CO_2 emissions, the reverse of policy intention. The implication for the wider construction industry is that the energy performance gap will remain an unavoidable consequence.

9.3 Contribution to Knowledge and Professional Practice

The energy performance gap in residential buildings is a growing field of research study. This research has provided a modest, but significant contribution to knowledge and practice by presenting evidence of the energy performance gap that can be observed, including the critical elements that have contributed to the gap. The research has identified a specific point in the project stage where the decisions to adopt the energy efficient and technological measures for that project are taken. Furthermore, the designer's motives and assessment methods that have informed these decisions has been identified as a potential early stage contribution to the energy performance gap. The research has identified where common assessment assumptions and professional opinions can be invalidated through analysis of operational data.

This research engaged with industry designers to gather data on their opinions and perceptions of key topics: including planning policy, energy assessment methods and the energy performance gap. The conclusions showed those responsible for implementing the policy do not expect that the assessed performance of heat networks and CHP or the scale of CO_2 emissions saved will be achieved in practice. Therefore, the 'credibility gap' has been identified at the earlier stages of a project, much earlier than described by Bordass (2004) or De Wilde (2014).

The opportunity to future proof a development to integrate LZC technologies is one of the primary motives for national and local government, as well as industry, to drive the implementation of heat networks. The research findings identified the potential future complexities of integrating small networks together to form large scale district energy networks. It has demonstrated that industry will need to understand the actual energy consumption of heat networks in order to successfully integrate future technologies and deliver intended CO_2 emission reductions.

As concluded in this research, there is growing evidence which has shown how energy and the resulting CO_2 emissions can be significantly higher in practice. Gas fired boilers and CHP emit NOx emissions. Therefore, the consequence of higher primary energy fuel consumption will be a higher level of NOx emissions released by these technologies.

9.4 Research Limitations and Future Research Opportunities

The conclusions presented in this thesis have demonstrated that the aim of answering the research questions has been achieved. However, there are three main limitations to this research. Firstly, the technological scope of the study was concentrated to the current dominant technology, heat networks and CHP. Reducing energy demand through energy efficiency is always the first step outlined in sustainable policy and the majority of the sustainable design literature. However, this element of sustainable design has already received attention from research (see Magalhães and Leal, 2014). Furthermore, the time and resources required to complete the appropriate field experiments (e.g. co-heating test), were not available to the researcher. While heat networks and CHP have been the most prolific technologies adopted by developers to meet the planning policy targets, there are examples (see chapter 2 and 6) of other LZC technology solutions being adopted. However, there is a lack of accessible energy data for these technologies. Therefore, the focus of the research was applied to heat networks and CHP, where heat metering (a requirement of the Heat Metering and Billing regulations) meant sufficient data was accessible. As the technological priority of the London Plan evolves, future research should follow the technological trends and apply the same level of scrutiny. The new draft London Plan (anticipated adoption in autumn 2019) is set to downgrade the prioritisation of CHP in favor of heat pumps (as part of a heat network), owing to the reduction in the grid carbon emission factor for grid electricity and the critical need to improve air quality. Future research should examine how heat pumps can be successfully integrated into heat networks and deliver the intended performance in practice, within the prescriptive approach of the London Plan energy policy.

Secondly, the content analysis of energy strategy documents was trialled on a relatively small sample and the case study focused on a single critical case. This has limited the amount of data collected and analysed as part of this research. The scope responded to time constraints and availability of the required detailed data. However, the data collected was sufficient to identify consistent and common trends to answer the research questions. Potentially more empirical data would provide additional evidenced based feedback to the house building industry and policy makers identifying the under performance and success of particular technologies and policies that drive their adoption.

Finally, the surveys were trialled on a relatively small stakeholder group, which has limited the range of perspectives collected and analysed as part of this research. The size of the stakeholder group was limited due to the results of the pilot study that identified that the wider stakeholder groups did not have the detailed experience and expertise required to answer the particular focus of the research. Additional evidence might have been collected through in-depth interviews with experienced stakeholders, but time constraints prevented this. Conversely, the mixed methods used here provided triangulation and reliability of the findings and conclusions.

9.5 Chapter Reflection

This final chapter has brought together the findings of the research and the conclusions drawn. The contribution of the findings for research and industry were outlined. The limitations of the research have been discussed together with opportunities for future research in this field.

BIBLIOGRAPHY

AECOM. (2014). *Seager Distillery Site Housing Development – Final Report. Domestic Buildings Phase 2: In-use Performance & Post-Occupancy Evaluation.* Building Performance Evaluation. Innovate UK. Building Data Exchange.

Allison, S. Bird, J. Ozmumcu, A. (2016). *An Operational Lifetime Assessment of the Carbon Performance of Gas Fired CHP led District Heating.* CIBSE Technical Symposium, London, UK 14-15 April 2016.

Amaratunga D. Baldry D. Sarsahar M. Newton R. (2002). *Quantitative and qualitative research in the built environment: Application of 'mixed' research approach.* Work Study Journal, 51 (1). pp. 17-31. ISSN 0043-8022 Available from: http://eprints.uwe.ac.uk/9190

Arksey, H. and Knight, P. (1999). *Interviewing for Social Scientists*. London: Sage. http://dx.doi.org/10.4135/9781849209335

Association for Decentralised Energy. (No date). *Combined Heat and Power Guidance for Contractors, Consultants and Customers.* The Association for Decentralised Energy Publication. Available at: https://www.theade.co.uk/resources/publications [accessed 19.08.2018]

Association for Decentralised Energy. (2017). *ADE Consultation Response / SAP 2016.* The Association for Decentralised Energy Publication.

Atkinson, P. and Coffey, A. (1997). *Analysing Documentary Realities*. In D. Silverman (Ed.), Qualitative research: Theory, Method and Practice, London: Sage, 45–62.

Atkinson, P. and Coffey, A. (2004). *Analysing Documentary Realities*. In D. Silverman (Ed.), Qualitative research: Theory, Method and Practice (2nd ed.), London: Sage, 56–75.

Bentley Systems. (2017). *Bentley Hevacomp Version V8i*. Software. United States.

Birchall, S. (2011). *An Appraisal of the Performance of a 'Green' Office Building*. PhD Thesis, School of Civil Engineering, University of Leeds.

Blackwell, H. (2013). *Foiling the Great Escape*. CIBSE Journal. Charter Institute of Building Services Engineers, August 2013.

Blaikie, N. (2003). *Analysing Quantitative Data*. London. Sage Publications

Bonham-Carter, C. and Woods, P. (2006). *The Greatest CO_2 Savings is From CHP Fuelled by Biomass*. Technical and Practice, Faber Maunsell.

Bordass, W. (2004). Learning more from what we build. Designing Better Buildings, 1–9. Available at: www.usablebuildings.co.uk/Pages/Unprotected/LearningMoreFromWhatWeBuild.pd

Bordass, W. Cohen, R. Field, J. (2004). *Energy Performance of Non-Domestic Building: Closing the Credibility Gap*. Building Performance Congress, Frankfurt, April 19-24, 2004.

Bowen, G. A. (2009). *Document analysis as a qualitative research method*. Qualitative Research Journal, 9(2), 27-40. DOI:10.3316/QRJ0902027

Brand, M. Della, A. and Svendsen, S. (2014). *Energy-efficient and cost-effective in-house substations bypass for improving thermal and DHW (domestic hot water) comfort in bathrooms in low-energy buildings supplied by low-temperature district heating.* Energy 67 (2014) 256-267.

Braun, V. and Clarke, V. (2006). *Using Thematic Analysis in Psychology*. Qualitative Research in Psychology, 3: 77–101.

Brown, C. (2015). *The Power of qualitative data in post-occupancy evaluations of residential high-rise buildings.* Journal of Housing and the Built Environment. DOI: 10.1007/s10901-015-9481-2. ISSN 1566-4910.

Brown, K. and Minett, S. (1996). *History of CHP developments and Current Trends*. Applied Energy 53. Great Britain: Elsevier Science Limited.

Bryman, A. (2004) *Social Research Methods*. Oxford, Oxford University Press.

Bryman, A. (2008). *Social Research Methods.* Third. Oxford University Press.

Building Engineering Services Assoication (BESA). (2017). *Good Practice Guide TR/37: Installation of Combined Heat and Power.* BESA Publications.

Building Research Establishment (2005). *Eco-homes 2005 – the environmental rating for homes, The Guidance*. Issue 1.1. 2005. Building Research Establishment. UK.

Building Research Establishment (2005a). *Standard Assessment Procedure for the Energy Rating of Dwellings*. 2005 edition. Crown, UK.

Building Research Establishment (2012). *The Government's Standard Assessment Procedure for Energy Rating of Dwellings.* 2012 edition. Crown, UK.

Building Research Establishment (2016). *Consultation Paper 04 – Distribution Loss Factor for Heat Networks Supplying Dwellings in SAP.* Issue 1.0. Building Research Establishment. UK.

Bunn, R. and Burman, E. (2015). *S-Curves to Model and Visualise the Energy Performance Gap between Design and Reality – First Steps to a Practical Tool.* CIBSE Technical Symposium 2015.

Burzynski, R. Crane, M. Yao, R. Becerra, V. (2012). *Space Heating and Hot Water Demand Analysis of Dwellings Connected to District Heating Scheme in the UK.* Central South University Press and Springer-Verlag Berlin Heidelberg, 2012.

Carbon Trust. (2004). *GPG388 – Good Practice Guide: Combined Heat and Power for Buildings*. Her Majesty's Stationary Office. 2004.

Carbon Trust. (2011). *CTG047 - Closing the Gap.* Her Majesty's Stationary Office. 2011.

Catto, I. (2008). *Carbon Zero Homes UK Style*. Renewable Energy Focus 9(1): 28–29.

European Committee for Standardization (CEN) 2007. *Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies - Part 4-5: Space heating generation systems, the performance and quality of district heating and large volume systems*. EN-15316-4-5, European Union Standard 2007.

Charter Institute of Building Services Engineers (CIBSE) (2013). *Combined Heat and Power for Buildings*. Application Manual 12 (AM12). London: Chartered Institute of Building Services Engineers.

Charter Institute of Building Services Engineers (CIBSE) (2015). *Heat Networks: Code of Practice for the UK.* London: Chartered Institute of Building Services Engineers.
CIBSE Certification (2017). *Become a CIBSE Certified Low Carbon Consultant.* [Online] Available at: https://www.cibsecertification.co.uk/Registration/Become-a-CIBSE-Low-Carbon-consultant [Accessed: 5th October 2018].

Citizens Advice. (2016). *District Heating Networks: Analysis of Information Request, 2016.* Citizens Advice UK.

Colmenar-Santos, A. Rosales-Asensio, E. Borge-Diez, D. Blanes-Peiró, J. (2016). *District heating and cogeneration in the EU-28: Current situation, potential and proposed energy strategy for its generalisation*. Renewable and Sustainable Energy Reviews 62 (2016) 621–639.

Cohen, L. Manion, L. and Morrision, K. (2000). *Research Methods in Education.* British Journal of Educational Studies 48 (4):446-446 (2000).

Crane, M. (2018). *Gas CHP on heat networks – how to maximise and estimate carbon savings in operation.* CIBSE Technical Symposium, London, UK 12-13 April 2018.

Creswell, J. (2003). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches.* Second Edition. SAGE publications.

Creswell, J. (2009). *Research Design*. Second Edition. SAGE publications.

Dalla, R. Boulter, R. Church, K. and Svendsen, S. (2012*). District heating (DH) network design and operation toward a system-wide methodology for optimizing renewable energy solutions* (SMORES) *in Canada: A case study*. Energy. Volume 45, Issue 01, September 2012. Pages 960-974.

Day, T. Jones P. and Oagumka P. (2007). *Review of the Impact of the energy policies in the London Plan on applications referred to the Mayor (Phase 2) – Final Report.* London South Bank University 2007.

Day, T. Oagumka, P. and Jones, P. (2009). *Monitoring the London Plan Energy Policies - Phase 3 Part 1 Report.* London South Bank University, 2009.

Day, T. Ogumka P. Jones, P. and Dunsdon A. (2009a). *The use of the planning system to encourage low carbon energy technologies in buildings.* Renewable Energy 34.

Day, T. Ogumka P. Jones, P. and Dunsdon A. (2010). *Monitoring the London Plan Energy Policies - Phase 3 Part 2 Report.* London South Bank University 2010.

Delzendeh, E. Wu, S. Lee, A. and Zhou, Y. (2017). *The Impact of Occupants' Behaviours on Building Energy Analysis: A Research Review.* Renewable and Sustainable Energy Reviews 80 (2017) 1061-1071.

Department for Business, Energy & Industrial Strategy (BEIS) (2017). *Digest of United Kingdom Energy Statistics (DUKES)*. Available at: https://www.gov.uk/government/statistics/combined-heat-and-power-chapter-7-digest-of-united-kingdom-energy-statistics-dukes

Department for Business, Energy & Industrial Strategy (BEIS) (2018). *Heat Metering and Billing Regulations 2014 Notification Data: February 2017.* 2017.

Department of Communities and Local Government (DCLG). (2007). *Building a Greener Energy Future: Policy Statement.* London. Crown 2007.

Department of Energy and Climate Change (DECC). (2009). *The Potential and Costs of District Heating Networks.* London: Crown 2009.

Department of Energy and Climate Change (DECC). (2009a). *Heat and Energy Saving Strategy.* London: Crown 2009.

Department of Energy and Climate Change (DECC). (2011). *The Carbon Plan: Delivering our Low Carbon Future*. London: Crown 2011.

Department of Energy and Climate Change (DECC). (2013). *Summary Evidence on District Heating Networks in the UK*. London: Crown 2013.

Department of Energy and Climate Change (DECC). (2015). *Assessment of the Costs, Performance, and Characteristics of the UK Heat Networks.* Crown 2015.

Department of Environment, Food and Rural Affairs (DEFRA). (2007). *Analysis of the UK potential for Combined Heat and Power*. Available at: http://webarchive.nationalarchives.gov.uk/

Department of Environment Transport and Regions (DETR). (2000). *Climate Change – The UK Programme.* London: Crown 2000.

Department of Trade and Industry (dti). (2003). *Our Energy Future – creating a low carbon economy*. The Stationery Office 2003.

Department of Trade and Industry (dti). (2007). *Meeting the Energy Challenge A White Paper on Energy May 2007.* London: Crown 2007.

De Wilde, P. (2014). *The gap between predicted and measured energy performance of buildings: A framework for investigation*. Automation in Construction, 41: 40–49.

De Wilde, P. and Jones, R. (2014). *The Building Energy Peformance Gap: Up Close and Personal*. Building Performance Analysis Group, School of Architecture, Design and Environment, Plymouth University. 2014.

Dooley, L. (2002). *Case study research and theory building.* Advances in Developing Human Resources, 4(3): 335-354.

Dupe, C. Babus'Haq, R. and Probert, S. (1994). *CHP Systems for Blocks of Flats? A Financial Assessment.* Applied Energy 49: 301-315.

Ealing Council (2012). *Delivering Local Development 2011/2 Eighth Annual Monitoring Report*. Available at: https://www.ealing.gov.uk/downloads/download/560/annual_monitoring_report_amr

Ealing Council (2014). *Authorities Monitoring Report 2012-2013*. Available at: https://www.ealing.gov.uk/downloads/download/560/annual_monitoring_report_amr

Ealing Council (2015). *Authorities Monitoring Report 2013-2014*. Available at: https://www.ealing.gov.uk/downloads/download/560/annual_monitoring_report_amr

Energy Saving Trust (EST). (2005). *Energy Efficiency Best Practice in Housing – Community Heating Serves Luxury Private Apartments.* Energy Saving Trust.

Energy Saving Trust (EST). (2008). *The Applicability of District Heating for New Dwellings*. CE299.

Energy Saving Trust (EST). (2009). *Final Report: Insitu Monitoring of Efficiencies of Condensing Boilers and Use of Secondary Heating.* Energy Saving Trust. Contract Number GaC3563.

European Technology Development and Demonstration Program (EUDP). (2014). *Guidelines for Low-Temperature District Heating.* Danish Energy Agency R&D programme EUDP.

European Commission. (2018). *Guidance Note on Article 14 of Directive 2012/27 (SWD). (2013).* [Online] Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52013SC0449 [Accessed 15.08.2018].

European Commission (2018a). *2020 Climate & Energy Package*. [Online] Available at: https://ec.europa.eu/clima/policies/strategies/2020_en [Accessed 16.01.2018].

Evans, R. (1993). *Environmental and Economic Implications of Small-Scale CHP*. Energy Policy, 0301-4215. 1993. Butterworth-Heinemann.

Feenberg, A. (2003). *Modernity Theory and Technology Studies: Reflections on Bridging the Gap.* Modernity and Technology, MIT Press, 2003, p.73104.

Feldman, M. and March, J. (1981). *Information in Organisations as a Singnal and Symbol.* Administrative Science Quarterly, 26(2), 171-186.

Finney, K. Zhou, J. Chen, Q. Zhang, X. and Chan, C. (2013). *Modelling and Mapping Sustainable Heating for Cities.* Applied Thermal Engineering, 53 (2013), 246-255.

Flyvbjerg, B. (2006). *Five Misunderstandings About Case-Study Research*. Qualitative Inquiry, 12(2), 219–245.

Foddy, W. (1993). *Constructing Questions for Interviews and Questionnaires*: Theories and Practice in Social Research, Cambridge: Cambridge University Press.

Foster, S. Love, J. Walker, I. and Crane, M. (2016). *Heat Pumps in District Heating.* Department of Energy and Climate Change. Crown 2016.

Fragaki, A. Andersen, A. (2011). *Conditions for aggregation of CHP plants in the UK electricity market and exploration of plant size*. Applied Energy, 88 (11), 3930–3940.

Fragaki, A. Andersen, A. and Toke, D. (2008). *Do Liberalised Electricty Markets Help or Hinder CHP and District Heating> The Case of the UK.* Energy Policy 36 (2008) 1448-1456.

Fragaki, A. Andersen, A. and Toke, D. (2008a). *Exploration of Economical Sizing of gas Engine and Thermal Store for Combined Heat and Power Plants in the UK.* Energy 33 (2008) 1659-1670.

Gaze, C. (2014). *Lessions from AIMC4 for Cost-Effective Fabric-First Low-Energy Housing.* Technolgy Strtagey Board. Availble at: www.aimc4.com.

Gill, Z. Tierney, M. Pegg, I. Allan, N. (2010) *Measured Energy and Water Performance of An Aspiring Low Energy/Carbon Affordable Housing Site in the UK.* Energy and Buildings 43 (2011) 117-125.

Gillham, B. (2000). *Developing a Questionnaire*. First edition. London. Continuum. ISBN: 9780826447951.

Goulden, M. and Spence, A. 2015*. Caught in the middle: The role of the Facilities Manager in organisational energy use*. Energy Policy, 85, 280-287.

Grainger, C. (2016). *UK Spatial District Heating Analysis – Summary Report*. BuroHappold Engineering, UK.

Gray, D. (2013). *Doing Research in the Rreal World*. Sage Publications Ltd. Third edition (2013). ISBN-10: 1446295311. ISBN-13: 978-1446295311.

Greater London Authority. (2004). *Green light to clean power, The Mayor's Energy Strategy.* London: Greater London Authority 2004.

Greater London Authority. (2004a). *The London Plan – Spatial Development Strategy for Greater London.* London: Greater London Authority 2004.

Greater London Authority. (2006). *London Energy Partnership – London Carbon Scenarios to 2026.* London: Greater London Authority 2006.

Greater London Authority. (2006a). *Sustainable Design and Construction – The London Plan Supplementary Planning Guidance.* London: Greater London Authority 2006.

Greater London Authority. (2008). *The London Plan – Spatial Development Strategy for Greater London Consolidated with Alterations since 2004.* London: Greater London Authority 2008.

Greater London Authority. (2011). *Energy Planning – Monitoring the Impact of London Plan Energy Policies in 2010.* London: Greater London Authority.

Greater London Authority. (2011a). *The London Plan – Spatial Development Strategy for Greater London.* London: Greater London Authority 2011.

Greater London Authority. (2011b).*Energy Planning – GLA Guidance on Preparing Energy Assessments.* Greater London Authority 2011.

Greater London Authority. (2011c). *Decentralised Energy Capacity Study – Phase 1: Technical Assessment.* Greater London Authority 2011.

Greater London Authority. (2012). *Energy Planning – Monitoring the Implementation of London Plan Energy Policies in 2011.* London: Greater London Authority.

Greater London Authority. (2013). *Energy Planning – Monitoring the Implementation of London Plan Energy Policies in 2012.* London: Greater London Authority.

Greater London Authority. (2013a). *District Heating Manual for London.* London: Greater London Authority.

Greater London Authority. (2014). *Energy Planning – Monitoring the Implementation of London Plan Energy Policies in 2013.* London: Greater London Authority.

Greater London Authority. (2014a). *Energy Planning – GLA Guidance on Preparing Energy Assessments.* Greater London Authority 2014.

Greater London Authority. (2015). *Energy Planning – Monitoring the Implementation of London Plan Energy Policies in 2014.* London: Greater London Authority.

Greater London Authority. (2015a).*Energy Planning – GLA Guidance on Preparing Energy Assessments.* Greater London Authority 2015.

Greater London Authority. (2016). *Energy Planning – Monitoring the Implementation of London Plan Energy Policies in 2015.* London: Greater London Authority.

Greater London Authority. (2016a). *The London Plan – The Spatial Development Strategy for London Consolidated with Alterations since 2011.* London: Greater London Authority.

Greater London Authority. (2017). *Energy Planning – Monitoring the Implementation of London Plan Energy Policies in 2016.* London: Greater London Authority.

Greene, J. Caracelli, V. and Graham, W. (1998). *Towards a Conceptual Framework for Mixed Methods evaluation Designs*. Educational Evaluation and Policy Analysis, 11(3), 255-274.

Guru Systems. (2018). *Open Data.* [Online]. Available at: https://pinpoint.gurusystems.com/open_data/ [Accessed on 13.04.2018].

Hackney Council (2011). *Annual Monitoring Report 2010/11.* Hackney Council.

Hawkey, D. (2012). *District heating in the UK: A Technological Innovation Systems analysis*. Environmental Innovation and Societal Transitions, 5, 19–32.

Hawkey, D. Webb, J. and Winskel, M. (2013). *Organisation and governance of urban energy systems: district heating and cooling in the UK*. Journal of Cleaner Production, 50, 22–31.

Hammersmith & Fulham Council (2015). *Monitoring Report April 2014 to March 2015.* Hammersmith & Fulham Council.

Heat Network Metering and Billing Regulations. (2015). Crown 2015.

House Builders Federation (HBF). (2007). *Briefing: Further Alterations to the London Plan: The Panel's Report on the Examination in Public*. Available from: https://www.hbf.co.uk/library/publications-reports-home-builders-federation/

Housing Select Committee. (2015). *Overview and Scrutiny: Communal Heating Systems Review.* Housing Select Committee, Lewisham Council.

Hsieh, H-F. and Shannon, S. (2005). *Three Approaches to Qualitative Content Analysis.* Qualitative Health Research. 2005. 15: 1277. DOI: 10.11/1049732305276687.

Huang, Z. and Yu, H. (2014). *Approach for Integrated Optimization of Community Heating System at Urban Detailed Planning Stage.* Energy and Buildings 77 (2014) 103-111.

Islington Council (2015). *Annual Monitoring Report 2014*. Available at: https://www.islington.gov.uk/planning/planningpol/local_dev_frame/pol_amr

Islington Council (2016). *Annual Monitoring Report 2015*. Available at: https://www.islington.gov.uk/planning/planningpol/local_dev_frame/pol_amr

James, D. (2011). *Report of the Executive Head of Planning and Transport: Draft Replacement Plan Panel Report*. London Borough of Sutton 2011.

Jones, R. Fuertes, A. and De Wilde, P. (2016) *The Gap Between Simulated and Measured Energy Performance: A Case Study Across SIz Identical New-Build Flats in the UK.* Conference Paper.

Johnston, D. Miles-Shenton, D. and Farmer, D. (2015). *Quantifying the Domestic Building Fabric 'Performance Gap'.* Building Services Engineering Research and Technology. Volume: 36. Issue: 5. Pages: 614-627.

Keirstead, J. and Schulz, N. (2010). *London and beyond: Taking a closer look at urban energy policy*. *Energy Policy*, *38*(9), 4870–4879.

Kelly, S. and Pollitt, M. (2010). *An assessment of the present and future opportunities for combined heat and Power with district heating (CHP-DH) in the United Kingdon.* Applied Energy, 38, 6936-6945.

King, M. and Shaw, R. (2012). *Community Energy: Planning, Development and Delivery.* International District Energy Association 2012.

Kondidari, A. (2017). *The influence of architects on the operational performance of low energy buildings.* Dissertation. Cardiff University.

Krizek, K. Forysth, A. and Slotterback, C (2009*). Is There A Role for Evidence-Based Practice in Urban Planning and Policy?* Planning Theory and Practice, Vol.10, No.4, 459-478, 2009.

Laajalehto, T. Kuosa, M. Mäkilä, T. Lampinen, M. and Lahdelma, R. (2014). *Energy efficiency improvements utilising mass flow control and a ring topology in a district heating network*. Applied Thermal Engineering, 69(1-2), 86–95.

Li, P. Thomas, M. and Froese, G. (2018). Post-occupancy evaluation: state-of-the-art and state-of-the-practice review. Building and Environment, 2018. DOI: 10.1016/j.buildenv.2018.04.024.

Littlewood, R. Smallwood, I. and Davies, G. (2014). *Energy and Environmental Performance of the 'Abertridwr Community' – the First Winter Season*. Energy Procedia 62 (2014) 532-542.

London Energy Partnership (LEP). (2004). *London Renewables – Integrating renewable energy into new developments: Toolkit for planners, developers and consultants.* London: Greater London Authority 2004.

Lund, H. Hvelplund, F. Ingermann, K. and Kask, Ü. (2000). *Estonian energy system proposals for the implementation of a cogeneration strategy*. Energy Policy, 28(10): 729–736.

Lund, H. and Anderson, A. (2005*) Optimal Designs of small CHP Plants in a Market with Fluctuating Electricity Prices*. Energy Conversion and Management (2005) 46: 893-904.

Mackenzie, N. and Knipe, S. (2006). *Research Dilemmas: Paradigms, Methods and Methodology.* Issues in Educational Research, 16(2): 193-205.

Magalhães, S. and Leal, V. (2014). *Characterization of thermal performance and nominal heating gap of the residential building stock using the EPBD-derived databases:The case of Portugal mainland.* Energy and Buildings 70 (2014): 167-179.

Mayor of London. (2017). *Total Energy Consumption, Borough.* London Datastore, [Online]. Available at: https://data.london.gov.uk/dataset/total-energy-consumption-borough [Accessed 09.01.2018].

McGowen, F. Mitchell, C. and Skea, J. (1993). *Energy Policy: An Agenda for the 1990s. SPRU, University of Sussex*, Brighton.

McManus, A. Gaterell, M. and Coates, L. (2010). *The potential of the Code for Sustainable Homes to deliver genuine "sustainable energy" in the UK social housing sector.* Energy Policy, 38(4): 2013–2019.

Menezes, A. Cripps, A. Bouchlaghem, D. and Buswell, R. (2012). *Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap*. Applied Energy, 97: 355–364.

Min, Z. Morgenstern, P. and Marjanovic-halburd, L. 2016. *Facilities management added value in closing the energy performance gap*. International Journal of Sustainable Built Environment, 5, 197-209.

Ministry of Housing (2014). *Use of Planning Conditions.* GOV.UK [Online]. Available at: https://www.gov.uk/guidance/use-of-planning-conditions [Accessed 24.01.2018].

Monahan, J. (2013). *Housing and the Carbon Reduction: Can main-stream 'eco-housing' deliver on its low carbon promise*. The School of Environmental Sciences, University of East Anglia.

Mutshewa, A. (2010). *The use of information by environmental planners: A qualitative study using Grounded Theory methodology*. Information Processing & Management, 46(2): 212–232.

Mroz, T. (2008). *Planning Community Heating Systems Modernization and Developments.* Applied Thermal Engineering (2008) 28: 1844-1852.

Newton, K. and Van Deth, J. (2005). *Foundations of Comparative Politics: democracies of the modern world* (Second.). New York: Cambridge Univeristy Press.

National Grid (2018). *Calorific Value.* [online]. Available at: https://www.nationalgridgas.com/data-and-operations/calorific-value-cv [Accessed 22.11.2018].

National Housing Building Council (NHBC). (2009). *Community Heating and Combined Heat and Power.* National Housing Building Company Foundation. 2009.

National Housing Building Council (NHBC). (2012). *Low and Zero Carbon Homes: Understanding the Performance Challenge.* National Housing Building Company Foundation. 2012.

Nooraei, M. Littlewood, J. and Evans, N. (2013). *Feedback from occupants in 'as designed' low-carbon apartments, a case study in Swansea, UK*. MGEF-13 Mediterranean Green Energy Forum. Energy Procedia (2013) 446-455.

Nussbaumer, T. and Thalmann, T. (2014). *Status Report on District Heating Systems in IEA Countries.* International Energy Agency IEA Bioenergy Task 32 and the Swiss Federation Office of Energy. Zuric. ISBN 3-908705-28-2.

Nussbaumer, T. and Koppejan, J. (not date). *Biomass Combustion for District Heating – Relevance and Design Requirements.* Available at: http://www.ieabcc.nl/publications/statement_dhc.html [Accessed 11.02.2018].

Office of Deputy Prime Minister (ODPM). (2004). *The Planning Response to Climate Change.* London: Queen's Printer and Controller of Her Majesty's Stationery Office.

Office of Deputy Prime Minister (ODPM). (2004a). *Planning Policy Statement 22: Renewable Energy.* London: Crown 2004.

Office of Deputy Prime Minister (ODPM). (2004b). *Draft Planning Policy Statement 1: Creating Sustainable Communities.* London: Crown 2004.

Office of Deputy Prime Minister (ODPM). (2005). *Planning Policy Statement 1: Delivering Sustainable Development.* London: Crown 2004.

O'Leary, Z. (2004). *The Essential Guide to Doing Research*. London: SAGE Publications Ltd. First Edition. 2004.

O'Leary, Z. (2014). *The Essential Guide to Doing Your Research Project*. (second). Thousand Oaks, CA: SAGE Publications, Inc.

Olsen P. Lambertsen, H. Hummelshoj, R. Bohm, B. Christainsen, C. Sveden, S. Larsen, C. and Warm, J. (2008). *A New Low-Temperature District Heating System for Low-Energy Buildings.* The 11th International Symposium on District Heating and Cooling, 2008, Reykjavik, Iceland.

Oppenhiem, A.N. (1992). *Questionnaire Design, Interviewing and Attitude Measurement*. Second Edition. London: Pinter.

Oreszczyn, T. and Lowe, R. (2009). *Challenges for energy and buildings research: objectives, methods and funding mechanisms*. Building Research & Information, 38**:** 107-122.

Osmani, M. and O'Reilly, A. (2009). *Feasibility of Zero Carbon Homes in England by 2016: A House Builders Perspective.* Building and Envioronment 44 (2009) 1917-1924.

Packwood, A. (2002). *Evidenced Based Policy: Rhetoric and Reality.* Social Policy & Society 1:3, 267-272. 2002.

Pacot, P. and Reiter, S. (2011). *District Heating and energy indicators: a method to assess the link between urban planning characteristics and energy efficiency of district heating networks*. Local Environment: Managent & Analysis (LEMA), University of Liège, Belgium.

Patton, M. (1990). *Qualitative Evaluation and Research Methods*. Beverly Hills, CA: Sage.

Pasimeni, M. Petrosillo, I. Aretano, R. Semeraro, T. De Marco, A. Zaccarelli, N. and Zurlini, G. (2014). *Scales, Strategies and Actions for Effective Energy Planning: A Review*. Energy Policy, 65, 165–174.

Planning and Compulsory Purchase Act. (2004). Crown. Available at: https://www.legislation.gov.uk/ukpga/2004/5/pdfs/ukpga_20040005_en.pdf

Planning and Energy Act. (2008). Crown. Available at: http://www.legislation.gov.uk/ukpga/2008/21/pdfs/ukpga_20080021_en.pdf

Poputoaia, D. and Bouzarovski, S. (2010). *Regulating district heating in Romania: Legislative challenges and energy efficiency barriers.* Energy Policy, 38(7), 3820–3829.

Quiquerez, L. Lachal, B. Monnard, M. and Faessler, J. (2016). *The Role of District Heating in Achieving Sustainable Cities: Comparative Analysis of Different Heat Scenarios for Geneva*. Energy Procedia 116 (2017) 79-90.

Raslan, R. and Davies, M. (2012). *Legislating building energy performance: putting EU policy intopractice.* Building Research & Information, 40:3, 305-31.

Rezaie, b. and Rosen, M. (2012). *District Heating and Cooling: Review of Technology and Potential enhancements.* Applied energy 93 (2012) 2-10.

Russell, S. (1986). *The political shaping of energy technology: Combined Heat and Power in Britain*. Dissertation, University of Aston, Birmingham, UK

(PDF) The development of combined heat and power (CHP) in the United Kingdom: A case history of niche failure and resilience.

Russell, S (2010). *CHP and District Heating to the mid-1990s*. Background Paper for Heat and the City Programme, ISSTI, Univeristy of Edinburgh, Edinburgh, UK.

Ridder, HG. (2017). *The Theory Contrubution of Case Study Research Design.* Business Research. DOI 10.1007/s40685-017-0045-z.

Riley, M. Moody, C. and Pitt, M. (2009). *A review of the evolution of post-occupancy evaluation as a viable performance measurement tool.* The Annual Conference Liverpool BEAN, 1–12.

Rosa, D and Christensen, J. (2011). *Low-Energy District Heating in Energy-Efficiecnt Building Areas*. Energy 36 (2011) 6890-6899.

Rossman, G. and Wilson, B. (1991). *Numbers and Words Revisited: being shamelessly eclectic. Evaluation Review*, Vol. 9 No. 5, pp 627-43.

Rydin, Y (2010). *Planning and the Technological Society: Discussing the London Plan*. International Journal of Urban and Regional Research, Vol.34.2, 243-59, 2010.

Rydin, Y. Amjad, U. and Whitaker, M. (2007). *Environmentally Sustainable Construction: Knowledge and Learning in London Planning Departments.* Planning Theory & Practice, 8:3, 363-380.

Rylander, A. (2012). Pragmatism and Design Research – An Overview. Available from: www.designfakulteten.kth.se/sites/default/files/designfpragdesignrapport_18.4.pdf

Saunders, M. Lewis, P. and Thornhill, A. (2007) *Research Methods for Business Students*, 4th Edition. London: Prentice Hall.

Shepley, C. Langton, A. and Nixon, S (2007). *Examination in Public: Panel Report*. City Hall, London, 2007.

Sodagar, B. and Starkey, D. (2015). *The Monitored Performance of Four Social Houses Certified to the Code for Sustainable Homes Level 5*. Energy and Buildings 110 (2016) 245-256.

Stemler, S. (2001). An overview of content analysis. *Practical Assessment, Research & Evaluation*, 7(17). Available From: http://PAREonline.net/getvn.asp?v=7&n=17

Sustainable Energy Authority of Ireland (seai). (2015). *Cost Benefit Analysis of the potential for High-Efficiency Cogeneration and Efficient District Heating & Cooling in Ireland.*

Teddlie, C. and Tashakkori, A. (2009). *Foundations of Mixed Methods Research: Integrating Quantitative and Qualitative Approaches in the Social and Behavioral Sciences*. Sage, London.

University College London (UCL). (2014). *One Brighton- Ongoing Monitoring Final Report Domestic Buildings Phase 2: In-use Performance & Post Occupancy Evaluation.* Building Performance Evaluation, Innovate UK, reference number: 450009. Available at: https://buildingdataexchange.org.uk/report/One+Brighton+-+ongoing+monitoring/800/

Urban Planners with Renewable Energy Skills (UP-RES). (No Date). *Energy Distribution: District Heating and Cooling – DHC.* [Online] Available at: https://www.euroheat.org/ [Accessed 08.04.2018].

Vesterlund, M. Sandberg, J. Lindblom, B. and Dahl, J. (2013). *Evaluation of Losses in District Heating System, a Case Study.* Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. China, July 16-19, 2013.

Van Dronkelaar C. Dowson M. Burman E. Spataru C. and Mumovic D. (2016). *A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings*. Front. Mech. Eng. 1:17.doi: 10.3389/fmech.2015.00017.

Watts, B. (2015). *Is it Time to Answer Those Awkward Questions on CHP and District Heating?.* Construction Magazine October 2015. Available at: http://www.constructionmanagermagazine.com/opinion/it-time-we-answ5ered-th9ose-awkw3ard-questions-chp/

Werner S. 2006. *Guidelines for Assessing the Efficiency of District Heating and District Cooling Systems*. Work Package 3, Euroheat&Power, Brussels, Belgium, pp. 1-8.

Williamson, J. (2012). *The Gap Between Design and Build: Construction Compliance Towards 2020 in Scotland.* Scottish Energy Centre, Edinburgh Napier University, 2012.

Woods, P. and Zdaniuk, G. (2011). *CHP and District Heating – how efficient are these technologies?.* CIBSE Technical Symposium. 2011.

Xing, Y. Bagdanavicius, A. Lannon, S. Pirouti, M. and Bassett, T. (2012). *Low Temperature District Heating Network Planning with Focus on Distribution Energy Losses.* International Conference on Applied Energy, Suzhou, China, ICAE2012-A101103.

Yang, X. and Svendsen, S. (2018). *Ultra-low temperature district heating system with central heat pump and local boosters for low-heat-density area: Analyses on a real case in Denmark*. Energy Journal, 2018. DOI:10.1016/j.energy.2018.06.068.

Yin, R. (2009). *Case Study Research*: Design and Methods. Fourth. Sage.

Yin, R. (2012). *Applications of Case Study Research*. Sage.

YouGen. (2015). *District Heating Networks May Not Be As Efficient as Hoped.* [Online]. Available at: http://www.yougen.co.uk/blog-entry/2316/District+heating+networks+may+not+be+as+efficient+as+hoped/ [Accessed: 22.04.2018].

Zero Carbon Hub (ZCH). (2013). *Closing the Gap between Design and As-Built Performance*. Interim Progress Report. July 2013. Available at: www.zerocarbonhub.org.

Zero Carbon Hub (ZCH). (2015). *Post-Occupancy Evaluation – Rowener Research Project Phase 2.* Available at: www.zerocarbonhub.org.

Zero Carbon Hub (ZCH). (2019). *Zero Carbon Policy.* Available at: http://www.zerocarbonhub.org/zero-carbon-policy/zero-carbon-policy

Zinko, H. Bohm, B. Kristjansson, H. Ottosson, U. Rama, M. and Sipila, K. (2008). *District Heating Distribution in Areas with Low Heat Demand Density.* IEA DHC Annex VIII. International Energy Agency.

Appendix 1 – Case Study – Summary of Meter Readings

Appendix Table 1.1: Domestic Heat Consumption

PLOT TYPE	Annual Heat Consumption	Annual Heat Consumption	Heat Consumption per Month (kWh)											
	$kWh/m^2/yr$	(kWh/year)	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15
T1	62.77	5263	252	40	4	205	318	400	842	998	756	548	444	456
T10	51.76	3509	56	43	41	36	149	275	616	486	732	665	185	225
T11	26.86	1789	75	63	63	46	81	119	327	363	318	207	67	60
T11	80.69	5374	225	144	176	243	321	554	721	780	756	705	518	231
T11	69.31	4616	96	118	120	143	160	418	594	755	648	565	506	493
T11	55.92	3724	101	57	81	99	112	215	597	712	730	746	219	55
T11	50.20	3343	114	62	48	85	133	189	578	518	577	513	358	168
T11	36.17	2409	101	59	35	70	52	98	210	275	250	407	478	374
T11	17.94	1195	14	20	24	24	27	77	172	279	260	185	70	43
T11	71.04	4731	101	56	23	105	323	469	891	977	785	615	296	90
T11	63.23	4211	76	95	146	109	235	348	695	685	603	346	455	418
T11	29.29	1951	31	23	14	21	42	129	322	493	423	293	120	40
T11	125.75	8375	787	477	621	536	474	580	761	893	933	855	766	692
T11	102.12	6801	369	256	198	188	335	780	1014	982	827	857	558	437
T11	98.08	6532	153	108	127	166	348	413	1009	1144	1092	908	563	501
T11	4.40	293	15	23	22	22	25	22	31	38	28	26	20	21
T11	72.03	4797	255	200	114	232	399	408	657	793	645	472	318	304
T11	30.89	2057	165	97	105	99	127	124	273	306	286	175	154	146
T11	47.00	3130	144	99	93	143	150	265	524	644	303	332	236	197
T11	81.46	5425	246	272	193	238	309	433	694	778	747	754	427	334
T13	102.67	6879	319	286	300	277	348	587	1017	937	887	732	644	545
T13	57.82	3874	176	132	137	157	143	231	348	408	592	614	521	415
T13	78.12	5234	268	245	217	257	269	386	716	795	812	673	235	361
T13	49.76	3334	53	39	48	44	106	411	565	653	544	504	216	151
T13	4.52	303	17	19	17	27	18	19	24	23	27	54	28	30
T13	17.87	1197	42	48	35	40	50	68	45	587	70	47	89	76
T13	69.87	4681	133	119	77	102	138	479	777	799	794	588	345	330
T13	60.12	4028	86	77	82	92	142	411	636	951	698	468	265	120
T13	20.13	1349	34	24	29	22	53	103	230	274	296	152	54	78
T13	21.37	1432	19	22	17	18	17	227	190	402	335	105	54	26
T13	70.72	4738	180	157	134	127	150	322	717	747	720	630	461	393
T13	40.55	2717	25	21	17	30	206	308	424	611	502	279	134	160
T14	55.21	3793	121	186	142	249	248	301	470	570	535	475	268	228
T14	38.72	2633	45	32	37	36	87	220	467	507	483	386	188	145
T14	47.42	3258	112	80	98	126	178	318	481	556	193	574	360	182
T14	20.86	1433	45	1	26	46	52	53	262	108	313	423	91	13
T15	105.85	7325	313	239	219	267	418	658	984	1058	1191	909	624	445
T15	32.62	2257	60	58	64	67	128	167	321	368	389	326	178	131
T16	28.88	2157	49	61	45	46	64	160	362	403	474	264	137	92
T16	26.89	2009	62	38	34	33	63	170	232	352	463	350	130	82
T16	21.98	1642	123	62	68	83	73	109	174	147	253	317	147	86

T16	25.92	1936	78	54	49	54	67	146	256	301	397	310	138	87
T18	59.22	4838	150	134	121	135	135	510	738	632	886	758	478	161
T18	15.21	1243	23	4	8	5	18	78	177	340	236	225	109	20
T18	42.41	3465	100	74	61	90	181	168	488	447	569	576	403	308
T18	63.53	5190	162	203	110	261	292	419	712	798	718	679	433	403
T19	40.57	3517.8	125	98	90	108	177	328	568	619	574	459	217	155
T19	41.20	3572	58	61	54	60	140	381	668	738	587	507	199	119
T19	24.06	2086	83	66	52	97	130	119	250	344	346	313	176	110
T19	51.08	4429	83	66	68	55	91	437	844	743	666	755	350	271
T19	37.81	3278	72	46	60	27	129	293	639	640	633	425	197	117
T19	48.72	4224	331	250	216	302	396	409	437	628	639	294	163	159
T2	41.59	1909	5	2	5	13	31	54	239	445	441	284	247	143
T2	68.28	3134	109	98	109	67	134	224	443	460	424	467	381	218
T2	87.10	3998	157	141	129	137	179	224	682	741	654	485	273	196
T2	18.71	859	24	36	25	42	43	71	76	107	147	102	78	108
T2	93.90	4310	132	38	39	104	127	312	769	940	885	560	244	160
T2	79.11	3631	78	80	81	100	136	427	552	783	721	316	237	120
T2	163.64	7511	171	92	75	176	386	757	1138	1178	1180	1144	734	480
T2	80.92	3714	114	90	79	96	160	317	544	647	613	503	324	227
T2	112.37	5158	121	134	111	127	164	421	699	776	825	883	515	382
T2	139.28	6393	281	222	43	42	199	625	1101	1076	1005	930	478	391
T2	31.09	1427	105	74	52	95	177	16	12	267	321	207	46	55
T2	31.66	1453	14	9	14	14	22	48	321	333	403	165	77	33
T2	70.72	3246	180	136	126	58	99	51	333	544	536	573	384	226
T2	90.78	4167	92	57	71	77	192	383	710	709	525	598	470	283
T2	37.41	1717	38	37	44	63	41	117	349	310	364	220	83	51
T2	128.47	5897	166	168	107	161	308	726	698	852	857	808	584	462
T2	105.90	4861	69	47	65	75	238	595	756	894	849	632	382	259
T2	80.92	3714	114	90	79	96	160	317	544	647	613	503	324	227
T2	63.57	2918	102	57	87	124	118	213	479	565	473	303	231	166
T2	68.28	3134	90	54	56	84	175	331	540	645	462	385	169	143
T2	103.86	4767	159	148	142	156	242	476	611	652	637	653	515	376
T2	51.29	2354	79	69	43	75	95	186	337	355	348	407	201	159
T2	125.03	5739	151	101	105	134	310	511	760	1013	963	606	598	487
T2	60.92	2796	84	111	127	106	113	204	363	580	476	331	201	100
T20	32.09	3703	62	47	45	49	193	279	492	596	630	564	386	360
T20	15.88	1833	92	102	95	108	120	108	166	409	270	158	123	82
T20	40.75	4702	176	118	119	171	353	380	612	739	661	574	438	361
T20	11.01	1270	10	15	14	19	20	135	181	201	455	148	39	33
T20	36.16	4173	102	101	78	69	196	337	494	714	806	624	386	266
T20	20.29	2341	114	52	83	78	123	173	322	402	413	290	164	127
T21	18.44	1820	68	47	73	73	76	100	218	304	303	324	148	86
T21	16.53	1632	18	12	16	19	19	135	59	387	378	381	118	90
T22	12.81	888	29	26	21	29	83	68	131	156	180	54	66	45
T23	19.64	1687	217	134	59	72	112	123	133	171	192	211	144	119
T23	44.38	3812	244	146	205	234	245	407	628	679	546	199	178	101

T24	43.73	2908	42	44	31	60	165	340	447	654	438	238	255	194
T24	45.73	3041	52	25	43	37	168	329	475	632	592	401	166	121
T25	16.87	1130	58	57	40	43	53	79	76	107	190	218	110	99
T25	27.56	1833	31	21	23	20	40	42	95	90	599	475	247	150
T25	18.13	1215	30	40	32	36	41	53	268	298	242	61	70	44
T25	48.16	3227	64	57	58	70	90	156	281	601	656	527	340	327
T26	45.02	2926	53	44	39	45	58	220	555	534	483	468	270	157
T27	203.64	9347	740	551	565	551	702	840	823	1037	1024	934	825	755
T27	80.44	3620	99	88	79	120	134	347	638	636	595	466	246	172
T27	53.81	2470	87	84	58	64	104	260	331	466	378	331	174	133
T27	112.11	5146	37	36	68	99	120	700	575	522	691	1118	718	462
T27	110.65	5079	108	89	104	101	167	301	997	1201	926	583	313	189
T28	107.32	4926	152	118	184	165	376	516	786	729	717	499	327	357
T28	60.33	2769	39	35	42	39	121	337	486	481	488	397	208	96
T28	74.79	3433	103	94	77	122	219	356	515	556	562	384	250	195
T28	54.51	2502	105	72	63	88	126	250	339	457	552	194	125	131
T28	76.73	3522	116	150	17	194	253	320	448	557	489	444	339	195
T3	102.62	4772	234	46	68	198	214	267	849	859	866	581	356	234
T3	43.74	2034	37	37	29	43	61	42	437	512	500	190	74	72
T3	62.88	2924	115	106	70	91	149	158	183	639	457	535	241	180
T3	53.55	2490	47	29	43	71	73	195	422	426	504	244	226	210
T3	44.40	2109	142	117	202	196	195	322	169	160	257	122	113	114
T3	108.32	5037	88	83	68	76	210	496	878	859	776	848	501	154
T3	94.47	4393	244	234	231	234	254	295	580	533	483	486	380	439
T30	12.57	842	365	278	131	28	21	10	9	0	0	0	0	0
T30	72.08	4793	230	211	158	192	258	371	674	715	572	534	457	421
T30	59.52	3988	131	134	196	120	190	333	712	740	704	460	146	122
T30	79.12	5301	147	132	160	140	211	505	998	948	760	655	320	325
T4	64.26	3906.75	91	61	84	89	201	379	584	693	656	571	273	226
T5	97.26	6001	130	74	127	166	385	761	852	968	933	846	445	314
T5	80.41	4961	129	89	124	113	285	559	780	785	720	631	382	364
T5	42.67	2633	42	30	19	25	34	64	417	648	623	495	134	102
T5	32.93	2032	64	50	66	51	99	131	286	371	346	312	131	125
T6	87.91	5134	76	52	75	79	218	442	833	887	839	707	553	373
T6	40.68	2376	34	25	34	39	45	135	434	471	444	382	217	116
T7	19.64	1271	57	52	13	11	14	46	55	192	324	369	115	23
T7	97.43	6304	324	276	269	266	334	464	751	938	941	769	517	455
T7	31.56	2042	35	30	21	21	35	190	375	448	473	325	50	39
T7	32.38	2095	37	26	37	60	86	181	377	404	431	254	94	108
T7	37.08	2399	50	37	39	43	59	233	548	467	444	420	23	37
T7	42.06	2721	61	54	41	65	170	310	434	369	375	394	257	191
T8	40.66	2659	51	50	49	51	75	149	500	590	507	354	186	97
T9	72.57	4666	206	232	202	172	194	141	658	679	870	597	429	286
T9	79.86	5135	280	265	266	279	305	320	789	834	650	424	376	347
T9	58.60	3768	182	187	180	198	173	231	548	694	443	367	361	204
T9	144.53	9293	273	209	230	191	457	992	629	1154	1532	1572	1105	949

T9	88.16	5669	335	301	294	315	284	442	826	1002	960	542	220	148
T9	125.86	8093	327	217	197	166	435	713	1311	1444	1319	1155	447	362
T9	133.23	8567	526	234	326	417	702	903	1048	903	889	1008	823	788
T9	29.58	1902	106	113	118	131	133	165	231	209	243	184	144	125
T9	60.08	3863	129	97	116	101	163	360	564	609	582	462	369	311

Appendix Table 1.2: Bulk Heat and Gas Consumption

Figure 7.1 Reference	Bulk Supply	Unit	Annual Consumption	Heat Consumption per Month (kWh)											
			(kWh/Year)	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15
G1	Bulk Gas	m3	132322	9107	8501	7132	5830	9514	12125	15778	16524	15447	13897	9114	9353
H3	Bulk Heat	kWh	1082500	61200	54300	56300	56800	73600	91600	127600	138600	129500	121800	90800	80400
H4	Circuit 1 Heat	kWh	120230	6980	5900	6090	6560	8270	10250	13710	15330	14040	13420	10290	9390
H5	Circuit 3 Heat	kWh	653200	33200	29700	31200	31200	41100	55500	80900	88000	82600	77900	54800	47100
H6	Circuit 4 Heat	kWh	232290	14550	12790	13170	13160	15900	19030	27120	27970	27170	24810	19080	17540

Appendix Table 1.3: Bulk Electrical Meter Readings and Consumption

Meter Reading Date	Reading kWh	Consumption kWh	Days Between Readings	Average Consumption kWh/day
10.07.14	318,185.5	-	0	-
05.11.14	339,692.5	21,507.0	119	180.73
07.12.14	345,501.0	58,08.5.0	32	181.52
22.12.14	348,232.0	2,731.0	15	182.07

Appendix 2 – Case Study - Summary of SAP Worksheet Results

Appendix Table 2.1: Summary of SAP 2005 Worksheet Results

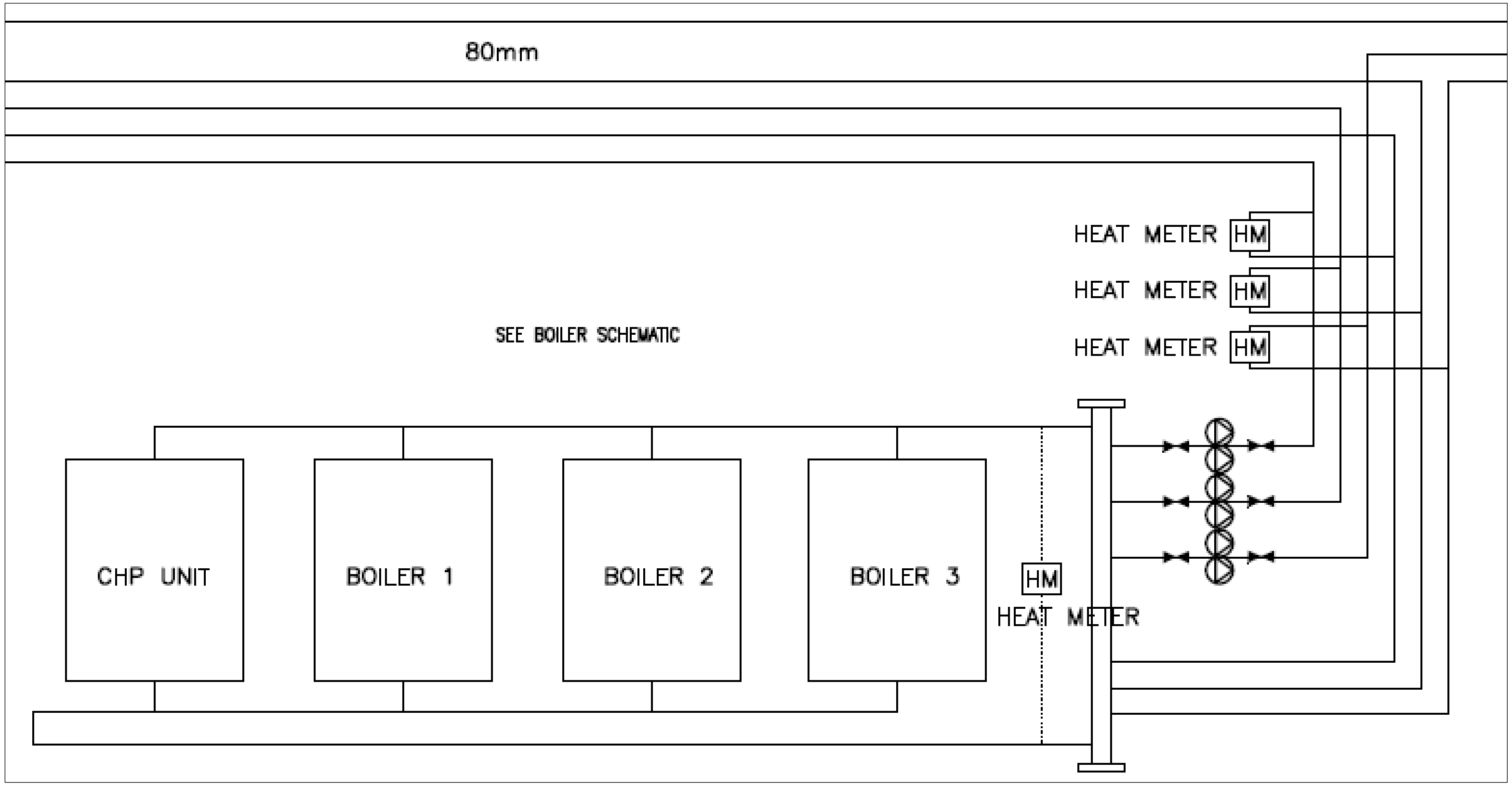
SAP Box:		box 5	box 51	box 81	box 82*	box 83*	box 84*	box 85*	box 86*	box 87*	box 87a*	box 87b*	box 88*	box 37	box 79	box 80
Type	Size	Area	HWS Output	Space HTG	Overall System Efficiency	Fraction CHP	Fraction of Boilers	Distribution Loss Factor	Space HTG CHP	Space HTG Boilers	HWS CHP	HWS Boilers	Electricity Fans & Pumps	Heat Loss Coefficient	Base Temperature	Degree Days
		m^2	kWh/yr	kWh/yr	%	-	-	-	kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	$W/(m^2k)$	^oC	-
T1	2B_4P	84	2948.64	3944.19	100.00	0.04	0.96	1.10	173.54	4165.07	129.74	3113.76	0.00	120.09	12.11	1368.47
T11	2B_4P	67	2682.00	1754.87	100.00	0.04	0.96	1.10	77.21	1853.15	118.01	2832.20	0.00	77.08	9.99	948.58
T11	2B_4P	67	2682.00	1754.87	100.00	0.04	0.96	1.10	77.21	1853.15	118.01	2832.20	0.00	77.08	9.99	948.58
T24	2B_4P	67	2682.00	1754.87	100.00	0.04	0.96	1.10	77.21	1853.15	118.01	2832.20	0.00	77.08	9.99	948.58
T11	2B_4P	67	2689.54	1733.69	100.00	0.04	0.96	1.05	72.81	1747.56	112.96	2711.05	0.00	75.87	10.01	952.09
T11	2B_4P	67	2689.54	1733.69	100.00	0.04	0.96	1.05	72.81	1747.56	112.96	2711.05	0.00	75.87	10.01	952.09
T18	3B_5P	82	2928.96	2364.18	100.00	0.04	0.96	1.10	104.02	2496.58	128.87	3092.98	0.00	102.41	10.06	961.89
T18	3B_5P	82	2928.96	2364.18	100.00	0.04	0.96	1.10	104.02	2496.58	128.87	3092.98	0.00	102.41	10.06	961.89
T18	3B_5P	82	2928.96	2364.18	100.00	0.04	0.96	1.10	104.02	2496.58	128.87	3092.98	0.00	102.41	10.06	961.89
T30	2B_4P	67	2669.32	1823.22	100.00	0.04	0.96	1.10	80.22	1925.32	117.45	2818.80	0.00	78.36	10.10	969.49
T30	2B_4P	67	2669.32	1823.22	100.00	0.04	0.96	1.10	80.22	1925.32	117.45	2818.80	0.00	78.36	10.10	969.49
T30	2B_4P	67	2669.32	1823.22	100.00	0.04	0.96	1.10	80.22	1925.32	177.45	2818.80	0.00	78.36	10.10	969.49
T30	2B_4P	67	2669.32	1832.22	100.00	0.04	0.96	1.10	80.22	1925.32	117.45	2818.80	0.00	78.36	10.10	969.49
T16	2B_4P	75	2815.45	2135.39	100.00	0.04	0.96	1.10	93.96	2254.98	123.88	2973.88	0.00	91.45	10.12	972.89
T16	2B_4P	75	2815.45	2135.39	100.00	0.04	0.96	1.10	93.96	2254.98	123.88	2973.12	0.00	91.45	10.12	972.89
T16	2B_4P	75	2815.45	2135.39	100.00	0.04	0.96	1.10	93.96	2254.98	123.88	2973.12	0.00	91.45	10.12	972.89
T16	2B_4P	75	2815.45	2135.39	100.00	0.04	0.96	1.10	93.96	2254.98	123.88	2973.12	0.00	91.45	10.12	972.89
T11	2B_4P	67	2689.54	1829.73	100.00	0.04	0.96	1.05	76.85	1844.37	122.96	2711.05	0.00	75.87	10.29	1004.83
T11	2B_4P	67	2689.54	1829.73	100.00	0.04	0.96	1.05	76.85	1844.37	112.96	2711.05	0.00	75.87	10.29	1004.83
T2	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T2	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T2	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T2	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T2	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T2	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T27	1B_2P	45	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T27	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T28	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T28	1B_2P	46	2350.25	1461.75	100.00	0.04	0.96	1.10	64.32	1543.60	103.41	2481.86	0.00	59.98	10.34	1015.44
T11	2B_4P	67	2682.00	2157.31	100.00	0.04	0.96	1.10	94.92	2278.12	118.01	2832.20	0.00	86.62	10.46	1037.79
T11	2B_4P	67	2682.00	2157.31	100.00	0.04	0.96	1.10	94.92	2278.12	118.01	2832.20	0.00	86.62	10.46	1037.79
T24	2B_4P	67	2682.00	2157.31	100.00	0.04	0.96	1.10	94.92	2278.12	118.01	2832.20	0.00	86.62	10.46	1037.79
T11	2B_4P	67	2659.54	2013.11	100.00	0.04	0.96	1.05	84.55	2029.22	122.96	2711.05	0.00	80.13	10.51	1046.78
T11	2B_4P	67	2689.54	2013.11	100.00	0.04	0.96	1.05	84.55	2029.22	112.96	2711.05	0.00	80.13	10.51	1046.78
T15	2B_4P	69	2684.41	2097.91	100.00	0.04	0.96	1.10	92.31	2215.40	118.11	2834.73	0.00	83.10	10.54	1051.89
T8	2B_4P	65	2674.78	2059.59	100.00	0.04	0.96	1.10	90.62	2174.93	117.69	2824.57	0.00	81.56	10.54	1052.14
T9	2B_4P	64	2680.24	2076.70	100.00	0.04	0.96	1.10	91.37	2193.00	117.96	2830.33	0.00	81.78	10.57	1058.09
T9	2B_4P	64	2680.24	2101.45	100.00	0.04	0.96	1.10	92.46	2219.13	117.93	2830.33	0.00	81.78	10.64	1070.69
T9	2B_4P	64	2680.24	2101.45	100.00	0.04	0.96	1.10	92.46	2219.13	117.93	2830.33	0.00	81.78	10.64	1070.69

T14	2B_4P	69	2702.34	2145.85	100.00	0.04	0.96	1.10	94.42	2266.02	118.90	2835.67	0.00	83.37	10.64	1072.39
T14	2B_4P	68	2702.34	2145.85	100.00	0.04	0.96	1.10	94.42	2266.02	118.90	2853.67	0.00	83.37	10.64	1072.39
T14	2B_4P	69	2702.34	2145.85	100.00	0.04	0.96	1.10	94.42	2266.02	118.90	2853.67	0.00	83.37	10.64	1072.39
T14	2B_4P	69	2702.34	2145.85	100.00	0.04	0.96	1.10	94.42	2266.02	118.90	2853.67	0.00	83.37	10.64	1072.39
T25	2B_4P	67	2669.32	2329.57	100.00	0.04	0.96	1.10	102.50	2460.03	117.45	2818.80	0.00	90.17	10.67	1076.41
T25	2B_4P	67	2669.32	2329.57	100.00	0.04	0.96	1.10	102.50	2460.03	117.45	2818.80	0.00	90.17	10.67	1076.41
T25	2B_4P	67	2669.32	2329.57	100.00	0.04	0.96	1.10	102.50	2460.03	117.45	2818.80	0.00	90.17	10.67	1076.41
T7	2B_4P	65	2650.33	1946.90	100.00	0.04	0.96	1.10	85.66	2055.92	116.61	2798.75	0.00	74.32	10.75	1091.56
T7	2B_4P	65	2650.33	1946.90	100.00	0.04	0.96	1.10	85.66	2055.92	116.61	2798.75	0.00	74.32	10.75	1091.56
T7	2B_4P	65	2650.33	1946.90	100.00	0.04	0.96	1.10	85.66	2055.92	116.61	2798.75	0.00	74.32	10.75	1091.56
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.64	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T13	2B_4P	67	2698.50	2045.11	100.00	0.04	0.96	1.10	89.98	2159.64	118.73	2849.62	0.00	77.95	10.75	1093.20
T19	3B_5P	87	3006.21	2839.00	100.00	0.04	0.96	1.05	119.24	2861.71	126.26	300.26	0.00	107.93	10.77	1096.03
T19	3B_5P	87	3006.21	2839.00	100.00	0.04	0.96	1.05	119.24	2861.71	126.26	3030.26	0.00	107.93	10.77	1096.03
T2	1B_2P	46	2350.25	1599.49	100.00	0.04	0.96	1.10	70.38	1689.06	103.41	2481.86	0.00	60.61	10.79	1099.51
T2	1B_2P	46	2350.25	1599.49	100.00	0.04	0.96	1.10	70.38	1689.06	103.41	2481.86	0.00	60.61	10.79	1099.51
T20	4B_6P	115	3491.28	3801.78	100.00	0.04	0.96	1.10	167.28	4014.68	150.45	3610.76	0.00	142.07	10.87	1114.96
T20	4B_6P	115	3491.28	3801.78	100.00	0.04	0.96	1.10	167.28	4014.68	150.45	3610.76	0.00	142.07	10.87	1114.96
T9	2B_4P	64	2680.24	2299.48	100.00	0.04	0.96	1.10	101.18	2428.25	117.93	2830.33	0.00	85.72	10.88	1117.74
T11	2B_4P	67	2682.00	2604.56	100.00	0.04	0.96	1.10	114.60	2750.42	118.01	2832.20	0.00	96.79	10.90	1121.53
T18	3B_5P	82	2928.96	3416.68	100.00	0.04	0.96	1.10	150.33	3608.02	128.87	3092.98	0.00	126.80	10.91	1122.70
T11	2B_4P	67	2689.54	2592.51	100.00	0.04	0.96	1.05	108.89	2613.25	112.96	2711.05	0.00	95.69	10.94	1128.83
T11	2B_4P	67	2689.54	2592.51	100.00	0.04	0.96	1.05	108.89	2613.25	112.96	2711.05	0.00	95.69	10.94	1128.83
T3	1B_2P	47	2383.71	1742.79	100.00	0.04	0.96	1.10	76.68	1840.39	104.88	2517.20	0.00	64.03	10.97	1134.06
T3	1B_2P	47	2383.71	1742.79	100.00	0.04	0.96	1.10	76.68	1840.39	104.88	2517.20	0.00	64.03	10.97	1134.06
T3	1B_2P	47	2383.71	1742.79	100.00	0.04	0.96	1.10	76.68	1840.39	104.88	2571.20	0.00	64.03	10.97	1134.06
T20	4B_6P	115	3419.28	3982.13	100.00	0.04	0.96	1.10	175.21	4205.13	150.45	3610.76	0.00	146.13	10.98	1135.44
T20	4B_6P	115	3491.28	4014.29	100.00	0.04	0.96	1.10	176.63	4239.09	150.45	3610.76	0.00	146.13	11.02	1144.60
T20	4B_6P	115	3491.28	4014.29	100.00	0.04	0.96	1.10	176.63	4239.09	150.45	3610.76	0.00	146.13	11.02	1144.60
T20	4B_6P	115	3491.28	4014.29	100.00	0.04	0.96	1.10	176.63	4239.90	150.45	3610.76	0.00	146.13	11.02	1144.60
T19	3B_5P	87	3006.21	2986.91	100.00	0.04	0.96	1.05	125.45	3010.81	126.26	3030.26	0.00	107.93	11.07	1153.13
T26	2B_4P	65	2698.82	3151.45	100.00	0.04	0.96	1.10	138.66	3327.93	118.75	2849.96	0.00	112.96	11.11	1162.41
T22	2B_4P	69	2702.98	3365.34	100.00	0.04	0.96	1.10	148.07	3553.80	118.93	2854.35	0.00	120.51	11.12	1163.53
T19	3B_5P	87	3006.21	3060.25	100.00	0.04	0.96	1.05	128.53	3084.74	126.26	3030.26	0.00	109.50	11.12	1164.53
T2	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T2	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55

T2	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T2	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T2	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T2	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T27	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T27	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T27	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T28	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T28	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T28	1B_2P	46	2350.25	2069.69	100.00	0.04	0.96	1.10	91.07	2185.59	103.41	2481.86	0.00	73.61	11.16	1171.55
T2	1B_2P	46	2350.25	1893.38	100.00	0.04	0.96	1.10	83.31	1999.41	103.41	2481.86	0.00	67.00	11.19	1177.44
T2	1B_2P	46	2350.25	1893.38	100.00	0.04	0.96	1.10	83.31	1999.41	103.41	2481.86	0.00	67.00	11.19	1177.44
T2	1B_2P	46	2350.25	1893.38	100.00	0.04	0.96	1.10	83.31	199.41	103.41	2481.86	0.00	67.00	11.19	1177.44
T2	1B_2P	46	2350.25	1893.38	100.00	0.04	0.96	1.10	83.31	1999.41	103.41	2481.86	0.00	67.00	11.19	1177.44
T5	2B_3P	62	2599.36	2229.82	100.00	0.04	0.96	1.10	98.11	2354.69	114.37	2744.92	0.00	78.73	11.20	1180.03
T11	2B_4P	67	2689.54	2716.48	100.00	0.04	0.96	1.05	144.09	2738.21	122.96	2711.05	0.00	95.69	11.21	1182.81
T11	2B_4P	67	2689.54	2716.48	100.00	0.04	0.96	1.05	114.09	2738.21	112.96	2711.05	0.00	95.69	11.21	1182.81
T10	2B_4P	68	2774.98	3279.53	100.00	0.04	0.96	1.10	144.30	3463.18	122.10	2930.38	0.00	114.83	11.25	1190.01
T6	2B_3P	58	2559.43	2177.13	100.00	0.04	0.96	1.10	95.79	2299.05	112.61	2702.76	0.00	76.19	11.25	1190.68
T11	2B_4P	67	2682.00	3042.14	100.00	0.04	0.96	1.10	133.85	3212.50	118.01	2832.20	0.00	106.30	11.26	1192.49
T5	2B_3P	62	2599.36	2289.09	100.00	0.04	0.96	1.10	100.72	2417.28	114.37	2744.92	0.00	79.98	11.26	1192.49
T5	2B_3P	62	2599.36	2289.09	100.00	0.04	0.96	1.10	100.72	2417.28	114.37	3744.92	0.00	79.98	11.26	1192.49
T5	2B_3P	62	2599.36	2289.09	100.00	0.04	0.96	1.10	100.72	2417.28	114.37	2744.92	0.00	79.98	11.26	1192.49
T15	2B_4P	69	2684.41	2876.72	100.00	0.04	0.96	1.10	126.58	3037.82	118.11	2834.74	0.00	100.20	11.28	1196.29
T9	2B_4P	64	2680.24	2889.21	100.00	0.04	0.96	1.10	127.13	3051.00	117.93	2830.33	0.00	99.46	11.35	1210.36
T11	2B_4P	67	2689.54	2917.77	100.00	0.04	0.96	1.05	122.55	2941.11	122.96	2711.05	0.00	99.95	11.38	1216.32
T11	2B_4P	67	2689.54	2917.77	100.00	0.04	0.96	1.05	122.55	2941.11	112.96	2711.05	0.00	99.95	11.38	1216.32
T25	2B_4P	67	2669.32	3216.51	100.00	0.04	0.96	1.10	141.53	3396.63	117.45	2818.80	0.00	109.62	11.41	1222.62
T9	2B_4P	64	2680.24	2920.15	100.00	0.04	0.96	1.10	128.90	3038.68	117.93	2830.33	0.00	99.46	11.42	1223.32
T9	2B_4P	64	2680.24	2920.15	100.00	0.04	0.96	1.10	128.49	3038.68	117.93	2830.33	0.00	99.46	11.42	1223.32
T9	2B_4P	64	2680.24	2920.15	100.00	0.04	0.96	1.10	128.49	3038.68	117.93	2830.33	0.00	99.46	11.42	1223.32
T2	1B_2P	46	2350.25	2339.58	100.00	0.04	0.96	1.10	98.54	2365.00	103.41	2481.86	0.00	74.24	11.58	1256.9
T2	1B_2P	46	2350.25	2490.70	100.00	0.04	0.96	1.10	98.54	2365.00	103.41	2481.86	0.00	74.24	11.58	1256.90
T19	3B_5P	87	3006.21	4052.87	100.00	0.04	0.96	1.05	170.22	4085.29	156.26	3030.26	0.00	133.84	11.60	1261.77
T9	2B_4P	64	2680.24	3139.63	100.00	0.04	0.96	1.10	138.14	3315.45	117.93	2830.33	0.00	103.40	11.62	1265.14
T7	2B_4P	65	2650.33	2848.28	100.00	0.04	0.96	1.10	125.32	3007.78	116.61	2798.75	0.00	93.41	11.65	1270.58
T7	2B_4P	65	2650.33	2848.28	100.00	0.04	0.96	1.10	125.32	3007.78	116.61	2798.75	0.00	93.41	11.65	1270.58
T7	2B_4P	65	2650.33	2848.28	100.00	0.04	0.96	1.10	125.32	3007.78	116.61	2798.75	0.00	93.41	11.65	1270.58
T23	3B_5P	86	2997.09	3710.57	100.00	0.04	0.96	1.10	163.27	3918.37	131.87	3164.92	0.00	121.15	11.67	1276.19
T23	3B_5P	86	2997.09	3829.43	100.00	0.04	0.96	1.05	160.84	3860.07	125.88	3021.06	0.00	124.49	11.70	1281.70
T3	1B_2P	47	2383.71	2423.89	100.00	0.04	0.96	1.10	106.65	2559.63	104.88	2517.20	0.00	78.26	11.74	1290.54
T3	1B_2P	47	2383.71	2423.89	100.00	0.04	0.96	1.10	106.65	2559.63	104.88	2571.20	0.00	78.26	11.74	1290.54
T3	1B_2P	48	2383.71	2423.89	100.00	0.04	0.96	1.10	106.65	2559.63	104.88	2517.20	0.00	78.26	11.74	1290.54
T3	1B_2P	47	2383.71	2423.89	100.00	0.04	0.96	1.10	106.65	2559.63	104.88	2571.20	0.00	78.26	11.74	1290.54
T21	2B_3P	99	3610.42	4683.97	100.00	0.04	0.96	1.10	206.09	4946.27	139.06	3337.41	0.00	150.82	11.76	1294.05
T21	2B_4P	99	3144.74	4637.56	100.00	0.04	0.96	1.10	204.05	4897.26	138.37	3320.84	0.00	149.12	11.77	1295.83

T4	2B_3P	61	2651.26	2865.49	100.00	0.04	0.96	1.10	126.08	3025.95	115.07	2761.71	0.00	91.70	11.80	1302.04
T2	1B_2P	46	2350.25	2490.70	100.00	0.04	0.96	1.10	109.59	2630.18	103.41	2481.86	0.00	79.32	11.83	1308.35
T2	1B_2P	46	2350.25	2490.70	100.00	0.04	0.96	1.10	109.59	2630.18	103.41	2481.86	0.00	79.32	11.83	1308.35
T2	1B_2P	46	2350.25	2556.06	100.00	0.04	0.96	1.10	112.47	2699.20	103.41	2481.86	0.00	80.63	11.89	1320.86
T2	1B_2P	46	2350.25	2556.06	100.00	0.04	0.96	1.10	112.47	2699.20	103.41	2481.86	0.00	80.63	11.89	1320.86
T19	3B_5P	87	3006.21	4321.92	100.00	0.04	0.96	1.05	181.52	4356.50	126.26	3030.26	0.00	135.40	11.93	1329.96
T6	2B_3P	58	2559.43	3049.20	100.00	0.04	0.96	1.10	134.16	3219.95	112.61	2702.76	0.00	92.97	12.10	1366.53
Total		**8,920**	**366,841.51**	**331,054.02**	**-**	**0.04**	**0.96**	**1.09**	**14,477.83**	**344,804.91**	**16,128.36**	**382,378.76**	**0.00**	**-**	**-**	**-**

Appendix 3 – Case Study – Heat Network Schematic Extracts


80mm
HEAT METER HM
HEAT METER HM
HEAT METER HM
SEE BOILER SCHEMATIC
CHP UNIT
BOILER 1
BOILER 2
BOILER 3
HM
HEAT METER

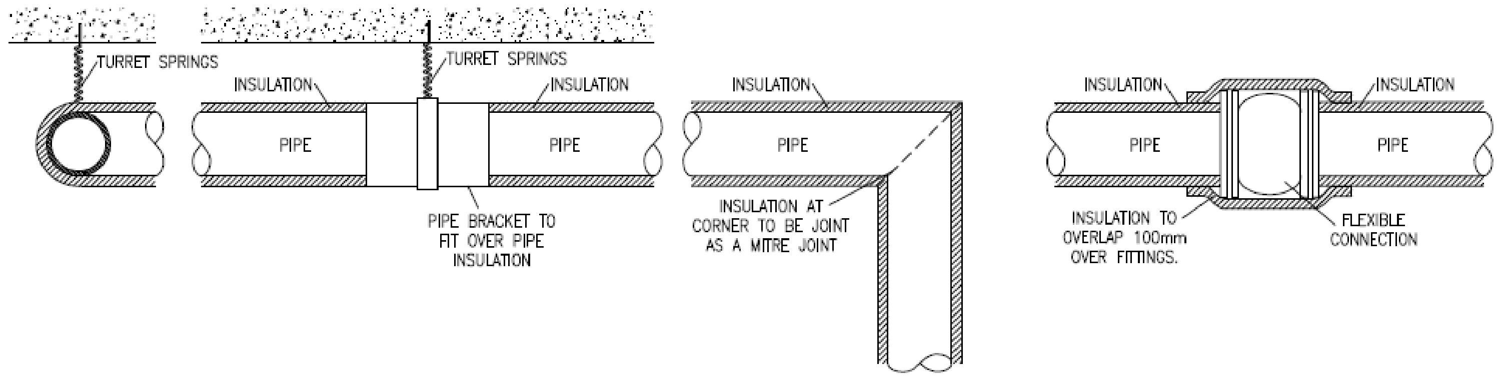
STEEL PIPEWORK SUPPORTS

TABLE C		
	MAX. SUPPORT INTERVAL	
PIPE SIZE mm	HORIZONTAL m	VERTICAL m
15	2.0	2.5
20	2.5	3.0
25	3.0	3.3
32	3.3	4.3
40	4.0	4.6
50	4.5	5.8
65	5.2	7.3
80	5.8	8.2
100	6.7	11.0
125	7.0	12.0
150	8.0	12.0
200	9.5	14.0
250	10.5	18.0

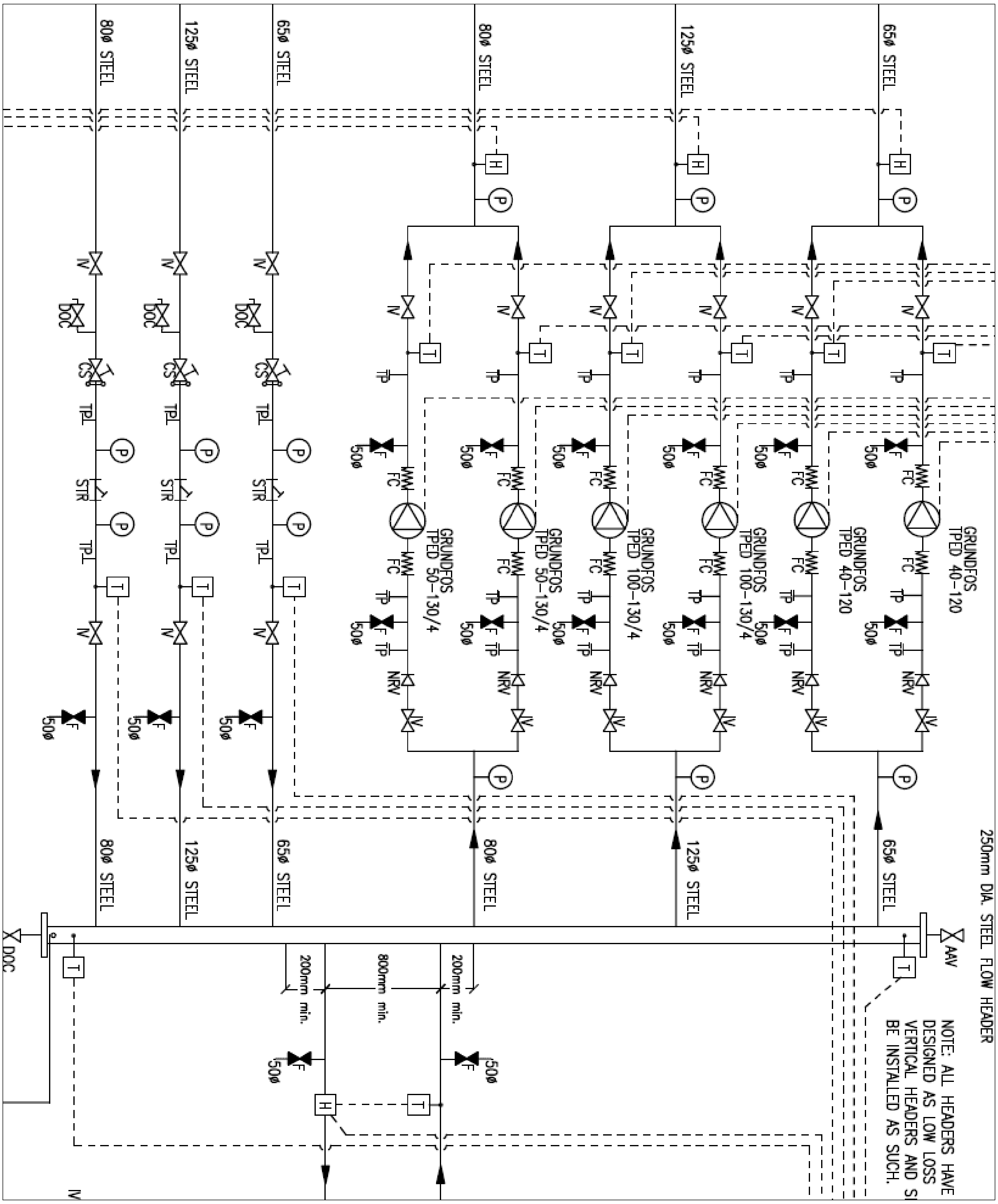
TABLE TAKEN FROM HVCA TR/20
PART 1 SECTION 3.7

NOTE: ALL PIPE WORK AND FITTINGS
TO BE INSULATED AS PER BUILDING REGULATION
L2A AS BELOW:

	MIN. INSULATION THICKNESS	
PIPE SIZE mm	MINERAL WOOL mm	PHENOLIC FOAM mm
15	30	15
20	30	15
25	35	20
32	35	20
40	35	20
50	40	25
65	40	25
80	40	25
100	45	25
125	45	30
150	45	30
200	50	30
250	50	30



INSULATION DETAILS TO PLANT ROOM – METAL CLAD IN ROCKWOOL



250mm DIA. STEEL FLOW HEADER
NOTE: ALL HEADERS HAVE
DESIGNED AS LOW LOSS
VERTICAL HEADERS AND SI
BE INSTALLED AS SUCH.
AAV
DOC
65ø STEEL
125ø STEEL
80ø STEEL
GRUNDFOS
TPED 40-120
GRUNDFOS
TPED 100-130/4
GRUNDFOS
TPED 50-130/4
IV
TP
FC
NRV
50ø
TPL
STR
CS
200mm min.
800mm min.

Appendix 4 – Case Study – Photographs

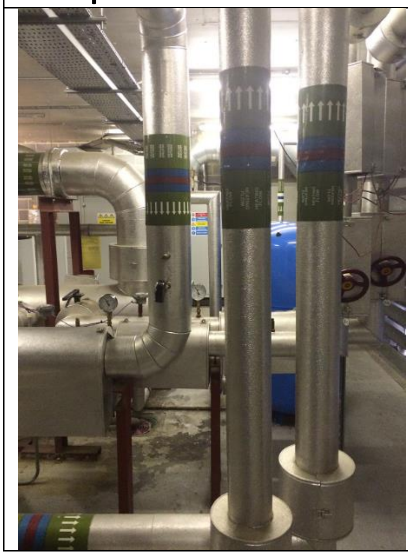
Primary Gas Meter	Primary Electrical Meter (10.07.2014)
	
Primary Electrical Meter (07.12.2014)	**Primary Electrical Meter (22.12.2014)**
	
Heat Network Bulk Heat Meter	**Heat Network Riser 3 Heat Meter**
	

Heat Network Riser 1 Heat Meter

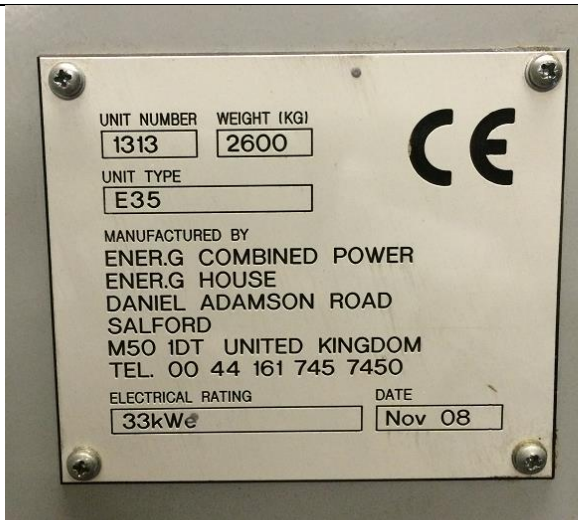
Heat Network Riser 4 Heat Meter

Example of Installed Insulation

Example of Installed Insulation



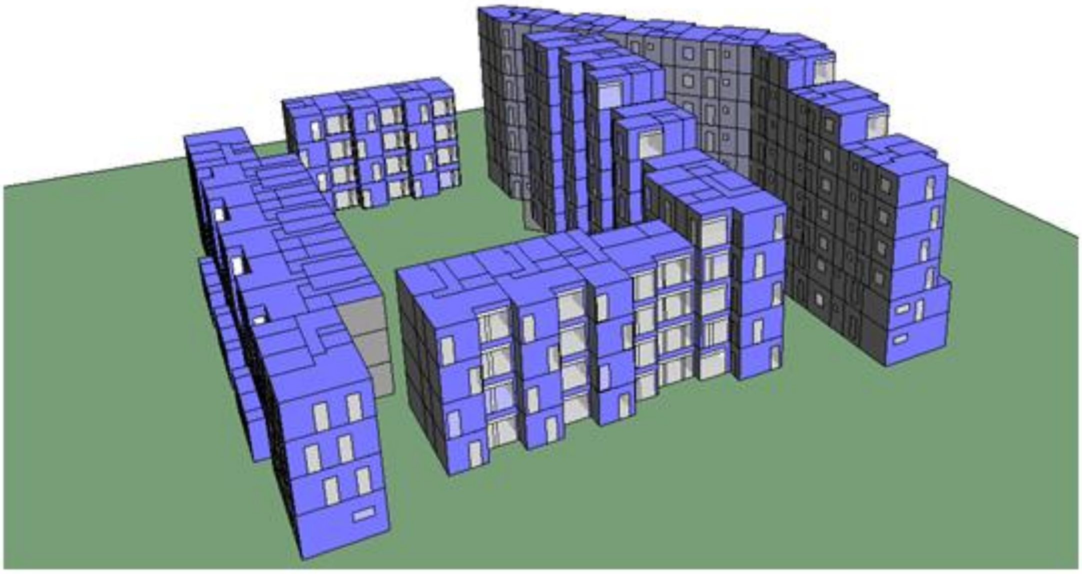
CHP Technical Data Plate



Appendix 5 – Case Study - Energy Strategy

SITE NAME REMOVED

ENERGY STRATEGY REPORT



AUTHOR DETAILS REMOVED

Contents

1.1 Introduction

1.1 This report has been prepared on behalf of **NAME REMOVED** to support an application submitted under Section 73 of the Town County Planning Act (1990), to vary Condition 20 attached to the planning permission for the redevelopment of **NAME REMOVED** regeneration area.

1.2 Condition 20 requires that "*No development shall take place until the applicant has provided to the Local Planning Authority a final detailed report (2 copies) for approval in writing identifying how a minimum of 10% of the energy requirements generated by the development will be achieved by renewable energy production methods. The approved scheme shall then be provided in accordance with these details prior to the first occupation of the development and thereafter retained for so long as the development remains in existence.*"

1.3 The report has been prepared following detailed discussions with senior officers of the London Borough of Southwark – Planning Deportment, over the nature and wording of this condition. It sets out to provide a robust, operational and financial assessment in support of the variation of this condition.

The Development

The **NAME REMOVED** development consists of 138 apartments in a single four linked blocks ranging from 4-8 stories. There is also a 300m^2 commercial unit on the ground floor, which has been earmarked for potential office usage.

The dwelling mix is:

1 Beds – 43
2 Beds – 77
3 Beds - 12
4 Beds - 6

2. EXECUTIVE SUMMARY

The Energy Demand generated by the proposed development is as follows:

kWh	Kg CO2 per annum	Carbon Dioxide (%)
Baseline emissions	**313,799.6**	
Savings from energy efficiency	**122,474**	**39%**
Savings from renewable energy	**20,640**	**10.79**

Key Energy Efficient Measures

There are a number of options which could be incorporated into the development to reduce carbon emissions. This report will assume the following energy efficient options are included:

- **Heat Recovery** installed within each apartment (£82,800) **saving 41.624 tonnes of CO_2 emissions.**
- **District Heating** (£276,000) **saving 52.515 tonnes of CO_2 emissions.**
- **CHP** (£100,000) **saving 28.334 tonnes of CO_2 emissions.**

This option would give total carbon savings of **121.474 tonnes of CO_2** (37%).

The total addtional cost for the project to install these energy efficient measures is **estimated at £458,800**.

Renewable Energy Inclusions

Considering the stage this scheme is currently at and that works are due to commence shortly, having considered all the renewable options recommend that **Option 1 – Photovoltaic arrays** is the most suitable for this building and the current planning status.

However this option is the most expensive at an estimated **£300,000** and requires **600m2** of roof space to mount the panels,. This will impact on the other sustainable elements of the scheme such as the Green and Brown roof covering. We also estimate that such a large area may not be feasible to accommodate and may require the roof over the atrium to include a semi transparent Photovoltaics (PV) covering. This would have design implications on the atrium space.

3. ENERGY DEMAND ASSESSMENT

The baseline scheme will be based on a gas fired boiler scheme to current Building Regulations (2006) - SAP results from each dwelling tenure multiplied by the numbers on the scheme. Each energy efficiency option has been re-modelled via SAP to calculate the Carbon savings.

Total energy efficiency savings vs baseline scheme (annual figures)

Energy efficiency measures of Heat recovery ventilation, District heating and Combined Heat and Power (CHP) have been modelled to give the savings in the chart below:

	1.3.1.1 Baseline Scheme (see assumptions and benchmarks below)	**1.8.1.2 Proposed scheme** (Incl. energy efficient design and technology)	**1.8.1.3 Change**
	Kg/CO_2	Kg/CO_2	
Total	**313,799**	**191,325**	**122,474**

Energy efficiency savings summary

	Amount	%
Reduction in CO_2 emissions	**122,474 Kg/CO_2**	**39**

Renewable energy savings
Carbon dioxide emissions reductions

Option 2 – with 600m2 of PV will give a 10.79% Carbon saving from renewables.

	Amount ($kg\ CO_2/year$)	%
Required CO_2 reductions from renewable	**19132**	**10**
Proposed CO_2 reductions from renewable:	**20,640**	**10.79**

4. ENERGY EFFICIENT DESIGN

The Mayor's Energy Strategy in the London Renewables Toolkit 2004 sets out an *Energy Hierarchy*, where reducing energy usage is the first consideration. This highlights a number of energy efficiency measures which can be instigated to reduce energy usage.

As many of these measures as possible have been considered but due to the Part L 2006 standards being 25% more onerous, the only feasible additional measure is as follows:

4.1 Heat Recovery Ventilation System

Ventilation and infiltration heat losses can account for over half of the heating load in commercial applications and tends to account for 40-50% of the heating load in residential applications. Large energy savings can be made by suitably controlling the amount of ventilation in a space and recovering the heat lost by controlled ventilation. Infiltration heat losses are impossible to control, but can be reduced by good quality workmanship at the construction stage.

The installation of heat recovery systems in residential apartments, as well as recovering heat, would eliminate the need for trickle vents, which are uncontrollable forms of ventilation. The super efficient Heat recovery ventilation can recover upto 95% of the heat lost during ventilation, however these units are expensive. The standard heat recovery units have an average efficiency of 75% and thus still making significant carbon savings.

The possible carbon savings from heat recovery would be around **17% or 41.624 tonnes of CO_2** using a 75% efficient unit.

The current market cost of heat recovery system is approximately £1,300 – £1,700 per apartment. However, this must be offset against the cost of acoustic trickle vents, mechanical ventilation. Downsizing of radiators should also offset against the cost of the system. This puts the installed extra cost of heat recovery at approximately £500-£700 per apartment.

Therefore for this site a **heat recovery ventilation system would cost an additional £82,800 if installed in all units.**

5.0 HEATING AND COOLING SYSTEMS

5.1 Cooling System

The scheme does not include cooling, as is not seen as energy efficient.

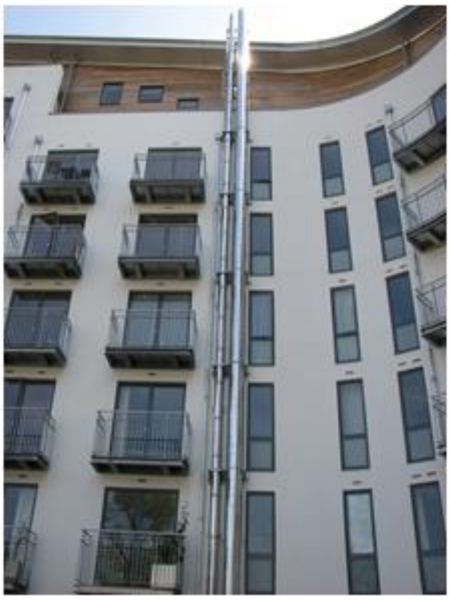
5.2 Heating System

a) **District Heating** – The advantages of this type of system is that it is generally more efficient than individual boilers (smaller diversified load with modular boilers working at most efficient load), are easier to maintain, and is future proof against emerging technologies and fuel types. The disadvantage of this type of system is that it significantly more expensive than individual boilers.

Calculated carbon savings of 17% could be realised with a district heating scheme if high efficiency boilers are installed, sized and controlled to work at maximum efficiency (approximately 94%).

The provision of district heating will result in an additional **17% carbon saving** or **52.515 tonnes of CO_2**.

In terms of costing, centralised boiler plant is generally of £2,000 per flat more expensive than individual boilers. **Total cost of an estimated £276,000.**



b) **<u>District Heating with Combined Heat and Power</u>**. The development does not lend itself to this form of technology because there is not a good mixed energy usage, allowing the continual running of the engine. However it is proposed install a small engine to offset some carbon on the scheme based on the summer time base load and we will also be exploring the possibility of connection of out scheme with others in the local area, which would allow the engine to run more hours per day.

The predicted summertime hot water boiler load falls around the 13kW mark for long periods. The closest commercially available CHP unit to fit this profile would be the ENER-G E35 unit. This has a thermal output of 55kW and an electric output of 33kW and can modulate to 50% of maximum output. This maximum thermal output is over twice the base load and so even if the unit was modulated to 50% some heat dumping may have to occur. This would mean that the installation would not conform to the Government's CHPQA standards and therefore Climate Change Levy exemption would not be applicable, however the carbon savings still are significant and worth including on larger housing schemes.

By the inclusion of CHP the tenants power and heat are controlled via a Energy Service company, the residents energy costs are guaranteed to be lower than a traditional system and are annually checked to keep costs down. The maintenance & performance targets are agreed at the start of the project to ensure a good service for all residence for the life of the plant.

The inclusion of this technology will still give an additional **9% carbon saving** or **28.334 tonnes of CO_2**.

The Cost for a 35kWe CHP engine and ancillary equipment is **estimated at £100,000.**

6. CONSIDERATION OF RENEWABLE ENERGY TECHNOLOGIES

After energy efficiency measures have been considered and incorporated into the scheme, the next step is to consider renewable technology, where feasible.

10% of site energy demand produced by renewable technologies would equate to offsetting a further **19,132 tonnes of CO_2.**

6.1 Photovoltaic Panels

From manufacturers data a 1 kW PV array will provide 800 kWh of electrical energy and cover an area of approximately 10m^2.

10% carbon savings for the energy efficient scheme could be achieved via a 60kW array. This would produce around 48,000 kWh per annum, offsetting **20,640 kg CO_2 per year**.

Space of 10 m2 per 1 kW array – meaning this site would need **600 m2 of PV.** This would mean almost all the roofs would have PV arrays and suggest the PTFE roof membrane to the atrium may need some semi transparent PV to make this installation more achievable or the Membrane.. The current market price for supply and installation of PV is approximately £5,000 per kW.

This would equate to a budget installed cost of £300,000; however, this figure could cost more if not mounted on the site's flat roofs, i.e. the PTFE roof was utilised.

6.2 Solar Water Heating

To provide 10% of total annual energy demand using a Central Solar Hot water system , a south-facing array with an area of 300m^2 would be required. This array would need to feed into the district heating scheme and therefore would conflict with the CHP operation and would need a large thermal store which the layout of the approved scheme has insufficient space for.

Without a large thermal store the scheme would require hot water cylinders with a secondary solar coil in each unit. This would need to be fed from a dedicated solar heating system- which is prohibitively expensive once you already have one district system. Furthermore the current scheme did not require cylinders and therefore the internal layout of the apartment has been planned accordingly- to meet lifetime homes standards and provide good storage for future residents, changing it at this stage would have a significant effect on apartment's bedroom and space provision.

Therefore with CHP, no opportunity to provide a large thermal store or cylinders in each unit this option would have to be discounted.

6.3 ¯ Wind Turbines

We suggest that a series of smaller roof-mounted turbines such as those manufactured by XCo2, which also claims to be "quiet", is most suited to this residential development.

Rather than the usual type of turbines, which seem to cause significant objections from local residents, a XCO2 QR5 -aesthetically pleasing turbines would be more suitable.

- Each unit is rated at 6kW – **XCO_2** QR5 wind turbine. (**5.5m high 3m in diameter, mounted on 3m pole**).

- 5 No. would be required at cost of approximately £25,000 each plus £10,000 installation costs. However they would need to be located such that they would not affect the wind flow to each unit.

The numbers needed for this site will result in wind flows conflicting with the turbines, making them less efficient. The solution would be one larger unit, but with 15m blades we are almost certainly not get permission due to the proximity of the railway lines.

These units would require planning amendment and the visual impact to this scheme would need to be assessed by the planners, so with the development about to proceed to construction we have to discount this option, as the delays to the project would affect the viability of the whole scheme.

The installation of 5 wind turbines would be an **estimated installed cost of £200,000.**

6.4 Ground Source Heat Pumps

It is proposed that the site is to proceed to piling within one month of this report being written. We estimate that system design and applications with the Environment Agency applications are likely to take a minimum of 3-6months.

The bore holes or thermal piles would need to be designed and approved by the EA before commencement of construction.

Taking this into account we would rule out ground source heat pumps for this scheme.

6.5 Biomass

A biomass boiler could potentially be incorporated into a communal heating scheme, but would require re-planning of the development at ground floor. The costs associated with this are almost exactly the same as those associated with district heating but with the added cost of fuel storage and the biomass boiler. Acquiring the fuel and transporting it to site are also further problems to overcome.

The scheme consists of 3 boilers and CHP engine as lead appliance. It is feasible to allow one of the boilers next inline to be a biomass feed appliance sized to cover 10% of the site energy demand. This central scheme would be installed on the ground floor with associated fuel hopper, etc. and distribution pipe work to the dwellings.

A large amount of plant space is required for this type of system which is currently not shown on the current approved layout. The hopper would need to be at the perimeter of the ground floor close to access roads for ease of delivery. We would envisage a delivery and ash removal of at least once a week. The hopper should be at road level which would be problematic with the current scheme.

The main concern with the installation of biomass on this scheme is the security of a local supply. Being an inner city development, the sourcing of local fuel on this scale could become a problem, with national or even international sourcing of fuel more likely. This tends to impact on the carbon savings of this technology due to transportation carbon emissions. In addition, due to the layout of the site, any delivery would have to be blown into a car park store, this limits delivery to wood pellets only and is a specialist delivery which may be difficult to source.

To integrate a biomass boiler capable of supplying 10% of the load into a communal heating system for the site would cost in the **region of £100,000** but we have discounted it for this scheme on the basis of the plant space required within the approved ground floor layout.

6.6 Biomass CHP

Installation of a biomass CHP engine has been considered, but the physical size and complexity of this type of plant is not practical in an installation below 1.5-2MW. This scheme has a peak load of 0.7MW and therefore it is not possible to consider it further at this time.

7. CONCLUSIONS AND COMMITMENTS

The following options are deemed to be the most feasible:

Option 1
10% carbon savings for the energy efficient scheme can be obtained via a 60kW array. This would produce around 48,000kWh per annum, offsetting **20,640 kg CO_2** per year.

The current market price for supply and installation of PV is approximately £5,000 kW.

This gives an installed cost of £300,000.

Option 2
The installation of a large wind turbine covering 10% of site would require 5No 6kW – **XCO_2** QR5 wind turbine. (5.5m high 3m in diameter, mounted on 3m pole).

Leaving a budget costing of **£200,000 for this option**.

CONCLUSIONS

Considering the stage this scheme is currently at and that we are proceeding to construction, recommend that **Option 1 – Photovoltaic arrays** is the simplest to integrate and will not cause great issues with the local residents and therefore the Local Planning Authority.

However the installation of PV panels would cost in the region £300,000 and requires 600m2 of roof, which may be difficult to include in the current scheme. We may require the PTFE roof over the covered atrium to include some semi transparent PV panels.

Along with the £458,800 for the energy efficiency measures mentioned in section 3 and the district heating & CHP in section 4 – the cost of meeting energy related planning conditions to this scheme stands at £758,800 excluding specialist consultants fees.

Appendix 6 – CUED Ethics Approval Letter

UNIVERSITY OF CAMBRIDGE
Department of Engineering

Dr Giovanna Biscontin
Chairman of the Ethics Review Committee

Chrisopher Marien

Division D

12 November 2018

Dear Mr Chrisopher Marien

Ethical Approval for your Research Project 'Design Intent Compared to Performance in Practice: The Case of Residential Heat Networks and Combined Heat and Power'

The Department's Research Ethics Committee has considered the documentation you provided in support of your research project in line with recommended procedures concerning ethical approval of research.

I am able to inform you that, with respect to ethical considerations, approval has been given to your project. Please note that this approval is based on the documentation you provided. You must re-submit your application to the Committee should you subsequently make any substantive changes relating to matters reviewed by the Committee.

We are content for this letter to be forwarded to your grant sponsors or to any partner institutions you may be working with if appropriate.

Yours sincerely

Giovanna Biscontin

Department of Engineering
University of Cambridge
Trumpington Street
Cambridge CB2 1PZ
research-ethics@eng.cam.ac.uk

Appendix 7 – Pilot Survey Focus Group Notes

Pilot Questionnaire Focus Group Feedback

Focus Group Participants:

Name Removed – Architect 1
Name Removed – Architect 2
Name Removed – Project Manager 1
Name Removed – Project Manager 2
Name Removed – Building Services Engineer 1
Name Removed – Building Services Engineer 2
Name Removed – Building Services Engineer 3
Name Removed – Building Services Engineer 4
Name Removed – Building Services Engineer 5
Name Removed – Building Services Engineer 6
Christopher Marien – PhD Candidate

Focus Group Introduction:
The focus group were welcomed and an introduction given. An outline of the PhD and the purpose of the questionnaire were discussed. The feedback was limited to 5 minutes per question to allow sufficient time and management of the discussion. The group were given a copy of the pilot questionnaire to aid feedback. The group were asked to firstly read each question and then provide any feedback.

SECTION:	**Introduction**
FEEDBACK:	The feedback from the group was that the introduction should be simplified to shorten it. The group’s opinion was that this section gave a clear set of instructions on how to complete the questionnaire. One participant suggested that not all respondents will have an understanding of what would be considered a ‘small-scale’ development. The group suggested ‘<500’ units was a suitable measure.
SECTION:	**Question 1**
FEEDBACK:	No comments received.
SECTION:	**Question 2**
FEEDBACK:	One participant suggested that this can be a tricky question to answer as it may involve multiple descriptions. It was suggest that a dropdown list stating key roles and activities would be easier for the respondents.
SECTION:	**Question 3**
FEEDBACK:	It was suggested that the ‘11 years of more’ answer provided ‘too wider scope’. It was possible that technology preferences, technology updates and government policy changes between generations and this may influence answers. Additional shorter ranges should be included.
SECTION:	**Question 4**
FEEDBACK:	The group suggested that this question was ambiguous. Some training may touch on low or zero carbon technologies but not be the specific focus. One participant questioned was unclear whether project experience counted.

SECTION:	**Question 5**
FEEDBACK:	Some of the architectural and project manager participants felt they struggled to understand the terms used.
SECTION:	**Question 6**
FEEDBACK:	Some of the architectural and project manager participants suggested that they had to make assumptions on answering these questions as they don't have the relevant experience. A 'don't know' option should be included.
SECTION:	**Question 7**
FEEDBACK:	Some of the architectural and project manager participants did not have the experience to answer accurately. Requires post-occupancy evaluation experience.
SECTION:	**Question 8**
FEEDBACK:	Some participants suggested that the question was open to interpretation by the respondent. The architectural and project manager participants felt it was outside their experience and expertise. The question contained too many statements, should be shortened.
SECTION:	**Question 9**
FEEDBACK:	The architectural and project manager participants felt it was outside their experience and expertise. The question requires a 'don't know' option.
SECTION:	**Question 10**
FEEDBACK:	The length of the question was suggested to be 'daunting' to some participants. The number of statements should be reduced.
SECTION:	**Question 11**
FEEDBACK:	The question was too ambiguous and would be different for each project.
SECTION:	**Question 12**
FEEDBACK:	The architectural and project manager participants felt the question was outside their experience and expertise.
SECTION:	**Question 13**
FEEDBACK:	Response was generally positive to the question. However, some participants felt some respondents would not have sufficient experience of each phase of a project.
SECTION:	**Question 14**
FEEDBACK:	The architectural and project manager participants felt they did not have sufficient post-occupancy evaluation experience to answer the question. One participant suggested that respondents should be asked if they have completed a post-occupancy study. Participants also generally felt there is little available industry information regarding post-occupancy evaluation.
SECTION:	**Question 15**
FEEDBACK:	Biased to a respondent's personal opinions. Need a 'Don't Know'

<u>End of Focus Group</u>

Appendix 8 – Industry Survey Questionnaire

UNIVERSITY OF CAMBRIDGE

A Survey of Energy Consultants - The Application of Energy Policy and the Energy Performance Gap

Introduction

"Thank you for taking part in this survey. This questionnaire forms part of my PhD research into the application of planning energy polices and the energy performance gap in low energy residential developments." - Christopher Marien

The questionnaire consists of 19 main questions which are divided into four sections. The questionnaire should not take longer than 15-20 minutes to complete. Please answer all questions.

As a thank you I will be making a donation to Cardiac Risk in the Young (www.c-r-y.org.uk) on the completion of the survey.

The following questions are designed to build an understanding on how local planning policies relating to energy are being applied in the formation of an energy strategy for new developments. The questions are focused on the analysis and selection of Low and Zero Carbon (LZC) technologies. Additionally, the questions try to gain an understanding of why particular LZC technologies are being selected over others and what the key drivers are behind their selection. Further questions are designed to gather opinions on whether predicted CO2 emission reduction targets are being achieved in practice.

The LZC technologies which are the focuses of this questionnaire are:
Solar water heating (with gas boiler for space heating)
Combined heat and power (with a heat network)
Heat Networks (district heating, communal heating)
Heat pumps – Air Source
Heat Pumps – Ground Source
Gas Condensing Boilers (combination and system)
Solar Photovoltaic
Wind Turbines
Biomass

Please answer the questions based on your own experiences. The questionnaire is focused on small scale multi-occupied developments (<500 dwellings) constructed from 2004 onward which have been subject to 'the London Plan' (2004 to 2016) response to climate change polices.

No personal information will be published or distributed.

Next

UNIVERSITY OF CAMBRIDGE

A Survey of Energy Consultants - The Application of Energy Policy and the Energy Performance Gap

Your Role and Experience

Please answer **all** questions before moving on to the next page.

* 1. Which of the following best describes the organisation you work in?

Please select one option from the drop down box below:

* 2. Which of the following best describes your job title?

Please select one option from the drop down box below:

* 3. How many years professional experience do you have?

Please select one option below:

- Less than 1 year
- 1 to 4 years
- 5 to 10 years
- 11 to 15 years
- 16 to 20 years
- 21 years or more

* 4. How many Energy Strategy reports have you created for planning applications?

Please select one option below:

- None
- Less than 5
- 6 to 10
- 11 or more

* 5. Have you had any formal education or training in 'Low or Zero Carbon' technologies?
Please select boxes as appropriate below:

- ☐ None
- ☐ Accredited Continuing Professional Development (CPD)
- ☐ BTEC
- ☐ Diploma Level
- ☐ Degree Level
- ☐ Post-graduate Degree Level
- ☐ CIBSE Low Carbon Consultant
- ☐ CIBSE Heat Networks Consultant
- ☐ SAP Assessor Qualified
- ☐ BREEAM Assessor Qualified
- ☐ LEED Assessor Qualified
- ☐ Other (please specify)

* 6. Which LZC technologies have been used on projects you have been involved with?
Please select one of the boxes below:

	Extensively	Limited	None	Don't Know	N/A
Solar Water Heating	○	○	○	○	○
Combined Heat and Power (CHP)	○	○	○	○	○
Heat Network	○	○	○	○	○
Air Source Heat Pumps	○	○	○	○	○
Ground Source Heat Pumps	○	○	○	○	○
Individual Gas Condensing Boiler	○	○	○	○	○
Solar Photovoltaic	○	○	○	○	○
Wind Turbines	○	○	○	○	○
Biomass	○	○	○	○	○

* 7. Have you completed a post-occupancy analysis on the energy performance of a building?
Please select one option below:

- ○ None
- ○ 1-3
- ○ 4-6
- ○ 7-10
- ○ More than 10
- ○ N/A

Energy Strategies for New Developments

Please answer **ALL** questions before moving on to the next page.

* 8. The creation of an Energy Strategy is a planning policy requirement for all new developments. Its purpose is to demonstrate predicted CO_2 emission reduction in comparison to Building Regulations Part L compliance. Planning policy sets a minimum CO2 emission reduction target. In your opinion, are the predicted CO_2 emissions savings being achieved in practice?
Please select one option below:

- ◯ CO2 emission reduction is achieving the reduction target set by the planning policy
- ◯ CO2 emissions are reduced compared to Building Regulations Part L compliance, but not achieving the policy target
- ◯ CO2 emissions are equal to Building Regulations Part L compliance
- ◯ CO2 emissions have not reduced compared to Building Regulations Part L compliance
- ◯ Don't Know
- ◯ N/A

* 9. The London Plan provides the following 'Energy Hierarchy' to guide developers when selecting technologies to increase CO_2 emissions savings:
1. Be Lean: use less energy (improved building fabric performance, low air leakage, low energy lighting and equipment)
2. Be Clean: supply energy efficiently (heat networks and CHP)
3. Be Green: use renewable energy (Photovolatics, Solar Thermal, Wind, Heat Pumps, Biomass)

Please rank which stage of the Energy Hierarchy you believe achieves the highest (1) to lowest (3) actual CO2 emission reductions in occupied developments?

- [ ] Be Lean: use less energy
- [ ] Be Clean: supply energy efficiently
- [ ] Be Green: use renewable energy

* 10. Have you recommended a heat network with CHP as the LZC technology for a new development in an Energy Strategy report?
Please select answers as appropriate below:

- ☐ Yes - as it was assessed to achieve the planning policy CO2 emissions reduction target based on SAP assessment
- ☐ Yes - as it was assessed to be a suitable technology for the development based on economic feasibility assessment
- ☐ Yes - as the developers preferred choice of technology
- ☐ Yes - as it was believed to be the only acceptable technology to planning officers
- ☐ Yes - as part of a wider off-site heat network
- ☐ No - as it was assessed not to achieve the planning policy CO2 emissions reduction target based on SAP assessment
- ☐ No - as it was assessed not to be a suitable technology for the development based on economic feasibility assessment
- ☐ No - as it was not the developers preferred choice of technology
- ☐ No- as it was believed not to be an acceptable technology to planning officers
- ☐ No - as there was no wider off-site heat network to support the development
- ☐ Don't Know
- ☐ N/A
- ☐ Other (please specify)

* 11. Have you completed the detailed design (RIBA Stage 4) of a heat network system with CHP for a new development?

Please select one option below:

- ◯ Yes
- ◯ No
- ◯ Don't Know
- ◯ N/A

Selection of Low and Zero Carbon (LZC) Technologies

Please answer **ALL** questions before moving on to the next page.

* 12. Considering the following statements, which best reflects your opinion/s of the process of selecting a LZC technology for a new low carbon development?

Please select the relevant scale for each statement below:

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	N/A
Planning policy and guidance prioritises the selection of certain LZC technologies over others	◯	◯	◯	◯	◯	◯
Adequate technical feasibility assessment is completed when selecting an LZC technology	◯	◯	◯	◯	◯	◯
Adequate life cycle costing assessment is completed when selecting an LZC technology	◯	◯	◯	◯	◯	◯
The type of LZC technology selected is most often driven by the developers' preference, rather than policy preference	◯	◯	◯	◯	◯	◯
The SAP assessment is a suitable tool to assess the performance of LZC technologies	◯	◯	◯	◯	◯	◯
An Energy Strategy is just a guidance document and further feasibility assessment should be completed during detailed design (Stage 4)	◯	◯	◯	◯	◯	◯
A LZC technology would be selected for a new development even where planning policy did not require the developer to do so	◯	◯	◯	◯	◯	◯

* 13. Considering the following statements, which best reflects your opinion/s on how a heat network (HN) with CHP should be assessed for an Energy Strategy?

Please select the relevant scale for each statement below:

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	N/A
Planning guidance provides sufficient information on how to adequately assess the feasibility of HN with CHP	○	○	○	○	○	○
Include a typical daily summer and winter thermal load profile	○	○	○	○	○	○
Finanical benifit from CHP electrcity export can always be expected	○	○	○	○	○	○
Capacity application for local gas and electrical infrastructure should be completed	○	○	○	○	○	○
HN with CHP is only selected when a development exceeds a minimum heat density (kWh/m2)	○	○	○	○	○	○
Accurate calculations of thermal distribution losses should be included	○	○	○	○	○	○
Life cycle costing compared to individual gas boilers should always be completed	○	○	○	○	○	○
Expected consumer heat tariff should be calculated	○	○	○	○	○	○
Final CHP size based on economical assessment of different CHP sizes.	○	○	○	○	○	○

* 14. To what extent have you used the following documents when considering the feasibility of a heat network with CHP for an Energy Strategy?

Please select the relevant scale for each document below:

	Extensively Used	Commonly Used	Limited Use	Not Used	Don't Know	N/A
The London Plan: Response to Climate Change	○	○	○	○	○	○
GLA: Sustainable Design and Construction SPG	○	○	○	○	○	○
GLA: District Heating Manual for London	○	○	○	○	○	○
GLA: Guidance on Preparing Energy Assessments	○	○	○	○	○	○
CIBSE: Heat Networks Code of Practice	○	○	○	○	○	○
CIBSE: AM12 Combined Heat & Power for Buildings	○	○	○	○	○	○
London Assembly: The London Heat Map online tool	○	○	○	○	○	○
CIBSE: Good Practice Guide 240: Community Heating	○	○	○	○	○	○

Role of the Energy Strategy in the Project Process

Please answer **ALL** questions before moving on to the next question.

* 15. In your experience, are any of the following aspects of an Energy Strategy changed post-planning during detailed design?

Please select the relevant scale for each technology below:

	Never	Seldom	Occasionally	Often	Always	Don't Know	N/A
Thermal performance of building elements (U-Values)	○	○	○	○	○	○	○
Designed air tightness	○	○	○	○	○	○	○
Solar energy transmittance of glazing (G-Value)	○	○	○	○	○	○	○
Ventilation strategy (MVHR, MEV, Passive Ventilation)	○	○	○	○	○	○	○
Heat Network to Individual Gas Boilers	○	○	○	○	○	○	○
Individual Boilers to a Heat Network	○	○	○	○	○	○	○
Inclusion of CHP	○	○	○	○	○	○	○
Exclusion of CHP	○	○	○	○	○	○	○
CHP specified output (kW)	○	○	○	○	○	○	○
Change of renewable technology type	○	○	○	○	○	○	○
Specified output/size (kW/m2) of renewable technology	○	○	○	○	○	○	○

* 16. In your experience, to what extent is the Energy Strategy document used during the different stages of the project?

Please select the relevant scale for each project stage below:

	Never	Seldom	Occasionally	Often	Always	Don't Know	N/A
Stage 1 – Preparation and Brief including Pre-Application Discussions	○	○	○	○	○	○	○
Stage 2 – Concept Design including Pre-Application Discussions	○	○	○	○	○	○	○
Stage 3 – Developed Design including Planning Application	○	○	○	○	○	○	○
Stage 4 – Technical Design	○	○	○	○	○	○	○
Stage 5 – Construction including commissioning	○	○	○	○	○	○	○
Stage 6 – Handover and Close Out	○	○	○	○	○	○	○
Stage 7 – In Use	○	○	○	○	○	○	○

* 17. In your experience, how involved is the original author/s of the Energy Strategy in the different stages of the project?

Please select the relevant scale for each project stage below:

	Never	Seldom	Occasionally	Often	Always	Don't Know	N/A
Stage 1 – Preparation and Brief	○	○	○	○	○	○	○
Stage 2 – Concept Design including pre-application discussions	○	○	○	○	○	○	○
Stage 3 – Developed Design including planning application	○	○	○	○	○	○	○
Stage 4 – Technical Design – post procurement	○	○	○	○	○	○	○
Stage 5 – Construction including commissioning	○	○	○	○	○	○	○
Stage 6 – Handover and Close Out	○	○	○	○	○	○	○
Stage 7 – In Use	○	○	○	○	○	○	○

The Energy Performance Gap

Please answer **ALL** questions before moving on to the next page.

* 18. Considering the following statements, which best reflects your opinion/s on the energy performance gap in new developments?

Please select the relevant scale for each statement below:

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	N/A
The energy performance gap is not an issue in new developments	○	○	○	○	○	○
The Energy Strategy document is suitable for comparison against actual in use energy consumption	○	○	○	○	○	○
Feedback is given to policy makers on actual in use performance of LZC technologies	○	○	○	○	○	○
Feedback to policy makers is ineffective regarding actual LZC technology performance	○	○	○	○	○	○
Inadequate feasibility assessment during planning stage creates unachievable performance in practice	○	○	○	○	○	○
Regulatory software for SAP Assessments is suitable for the assessment of LZC technologies	○	○	○	○	○	○

19. In your opinion, based on your experience of Heat Network with CHP systems, is there an energy performance gap between the planning stage Energy Strategy and actual performance in practice?

	Lower than predicted	Approximately the same as predicted	Higher than predicted	Don't Know	N/A
Distribution heat losses	○	○	○	○	○
Pumping energy consumption	○	○	○	○	○
Efficiency of heat generating plant	○	○	○	○	○
Consumers space and hot water heating requirements	○	○	○	○	○
Savings in CO2 emissions	○	○	○	○	○

Thank You

Thank you very much for taking part in this questionnaire, your time and participation is greatly appreciated. If you would be willing to take part in a one to one interview to discuss your answers and provide further information on the application of energy policy and the energy performance gap, please confirm below. Interviews will take approximately 30 minutes (either in person or by telephone) and all information collated will be kept confidentially.

* 20. Would you be willing to take part in a one to one interview?

- ○ **Yes**. I would like to take part in a follow up interview. My contact details are below.
- ○ **No**. I would not like to take part in a follow up interview.

21. If you clicked YES. Please enter your contact details below:

Name	
Email Address	
Phone Number	

Thank you again for your participation.

Christopher Marien
PhD Candidate
University of Cambridge
cnm29@cam.ac.uk
01689 888 8384

Appendix 9 – Survey Results

Q1	Which of the following best describes the organisation you work in? Please select one option from the drop down box below:										
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#0
	Private Developer	Housing Association Developer	Local Authority Developer	Building Services Engineering Consultancy	Energy Specialist Consultancy	Architectural Design	Low or Zero Carbon (LZC) Installer	Mechanical Installer	Electrical Installer	Planning Consultancy	Other (please specify)
Number of Responses	0	0	0	45	10	1	0	0	0	1	5
Percentage of Responses	0%	0%	0%	73%	16%	2%	0%	0%	0%	2%	8%

Q2	Which of the following best describes your job title? Please select one option from the drop down box below:											
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#0
	Energy Consultant	Mechanical Design Engineer	Electrical Design Engineer	Energy Assessor	Architect	LZC Installer	Mechanical Installer	Electrical Installer	Planning Consultant	Surveyor	Sustainability Consultant	Other (please specify)
Number of Responses	16	15	3	2	0	0	0	0	0	2	16	8
Percentage of Responses	26%	24%	5%	3%	0%	0%	0%	0%	0%	3%	26%	13%

Q3	How many years professional experience do you have? Please select one option below:					
	#1	#2	#3	#4	#5	#6
	Less than 1 year	1 to 4 years	5 to 10 years	11 to 15 years	16 to 20 years	21 years or more
Number of Responses	0	6	19	17	6	14
Percentage of Responses	0%	10%	31%	27%	10%	23%

Q4	How many Energy Strategy reports have you created for planning applications? Please select one option below:			
	#1	#2	#3	#4
	None	Less than 5	6 to 10	11 or more
Number of Responses	8	12	6	36
Percentage of Responses	13%	19%	10%	58%

Q5	Have you had any formal education or training in 'Low or Zero Carbon' technologies? Please select boxes as appropriate below:											
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	
	None	Accredited Continuing Professional Development (CPD)	BTEC	Diploma Level	Degree Level	Post-graduate Degree Level	CIBSE Low Carbon Consultant	CIBSE Heat Networks Consultant	SAP Assessor Qualified	BREEAM Assessor Qualified	LEED Assessor Qualified	Other (please specify)
Number of Responses	9	26	3	5	11	14	40	3	17	14	3	11
Percentage of Responses	15%	42%	5%	8%	18%	23%	65%	5%	27%	23%	5%	18%

Q6		Which LZC technologies have been used on projects you have been involved with? Please select one of the boxes below:								
		Solar Water Heating	Combined Heat and Power	Heat Networks	Air Source Heat Pumps	Ground Source Heat Pumps	Individual Gas Condensing Boilers	Solar Photovoltaics	Wind Turbines	Biomass
Exstensivley	#1	5	43	25	26	4	44	52	1	5
Limited	#2	48	18	30	28	34	15	8	14	39
None	#3	8	0	6	7	23	2	1	46	17
Don't Know	#4	0	0	0	0	0	0	0	0	0
N/A	#5	1	1	1	1	1	1	1	1	1

Q7	Have you completed a post-occupancy analysis on the energy performance of a building? Please select one option below:					
	#1	#2	#3	#4	#5	#6
	None	1-3	4-6	7-10	More than 10	N/A
Number of Responses	33	21	1	1	3	2
Percentage of Responses	53%	34%	2%	2%	5%	3%

Q8	The creation of an Energy Strategy is a planning policy requirement for all new developments. Its purpose is to demonstrate predicted CO2 emission reduction in comparison to Building Regulations Part L compliance. Planning policy sets a minimum CO2 emission reduction target. In your opinion, are the predicted CO2 emissions savings being achieved in practice? Please select one option below:		
9	15%	#1	CO2 emission reduction is achieving the reduction target set by the planning policy
33	53%	#2	CO2 emissions are reduced compared to Building Regulations Part L compliance, but not achieving the policy target
1	2%	#3	CO2 emissions are equal to Building Regulations Part L compliance
13	21%	#4	CO2 emissions have not reduced compared to Building Regulations Part L compliance
5	8%	#5	Don't Know
1	2%	#6	N/A

Q9 The London Plan provides the following 'Energy Hierarchy' to guide developers when selecting technologies to increase CO2 emissions savings:1. Be Lean: use less energy (improved building fabric performance, low air leakage, low energy lighting and equipment) 2. Be Clean: supply energy efficiently (heat networks and CHP)3. Be Green: use renewable energy (Photovolatics, Solar Thermal, Wind, Heat Pumps, Biomass)Please rank which stage of the Energy Hierarchy you believe achieves the highest (1) to lowest (3) actual CO2 emission reductions in occupied developments?

	Highest CO2 Reductions (#1)		Middle (#2)		Lowest CO2 Reductions (#3)	
Be Lean	38	61%	18	29%	6	10%
Be Clean	17	27%	23	37%	22	35%
Be Green	7	11%	21	34%	34	55%
	62		62		62	

Q10 **Have you recommended a heat network with CHP as the LZC technology for a new development in an Energy Strategy report? Please select answers as appropriate below:**

43	69%	Yes - as it was assessed to achieve the planning policy CO2 emissions reduction target based on SAP assessment
27	44%	Yes - as it was assessed to be a suitable technology for the development based on economic feasibility assessment
19	31%	Yes - as the developers preferred choice of technology
26	42%	Yes - as it was believed to be the only acceptable technology to planning officers
26	42%	Yes - as part of a wider off-site heat network
4	6%	No - as it was assessed not to achieve the planning policy CO2 emissions reduction target based on SAP assessment
9	15%	No - as it was assessed not to be a suitable technology for the development based on economic feasibility assessment
9	15%	No - as it was not the developers preferred choice of technology
2	3%	No- as it was believed not to be an acceptable technology to planning officers
13	21%	No - as there was no wider off-site heat network to support the development
0	0%	Don't Know
3	5%	N/A

Q11 **Have you completed the detailed design (RIBA Stage 4) of a heat network system with CHP for a new development? Please select one option below:**

#1	#2	#3	#4
Yes	No	Don't Know	N/A
31	27	0	4
50%	44%	0%	6%

Q12 **Considering the following statements, which best reflects your opinion/s of the process of selecting a LZC technology for a new low carbon development? Please select the relevant scale for each statement below:**

Strongly Disagree (#1)		Disagree (#2)		Neither (#3)		Agree (#4)		Stronly Agree (#5)		N/A (#6)		
Strongly Disagree		Disagree		Neither		Agree		Stronly Agree		N/A		
1	2%	1	2%	12	19%	27	44%	20	32%	1	2%	Planning policy and guidance prioritises the selection of certain LZC technologies over others
1	2%	12	19%	12	19%	27	44%	9	15%	1	2%	Adequate technical feasibility assessment is completed when selecting an LZC technology
7	11%	25	40%	16	26%	10	16%	3	5%	1	2%	Adequate life cycle costing assessment is completed when selecting an LZC technology
2	3%	11	18%	15	24%	30	48%	3	5%	1	2%	The type of LZC technology selected is most often driven by the developers' preference, rather than policy preference
17	27%	21	34%	15	24%	6	10%	2	3%	1	2%	The SAP assessment is a suitable tool to assess the performance of LZC technologies
2	3%	8	13%	6	10%	28	45%	16	26%	2	3%	An Energy Strategy is just a guidance document and further feasibility assessment should be completed during detailed design (Stage 4)
7	11%	15	24%	17	27%	20	32%	2	3%	1	2%	A LZC technology would be selected for a new development even where planning policy did not require the developer to do so

Q13 **Considering the following statements, which best reflects your opinion/s on how a heat network (HN) with CHP should be assessed for an Energy Strategy? Please select the relevant scale for each statement below:**

Strongly Disagree (#1)		Disagree (#2)		Neither (#3)		Agree (#4)		Stronly Agree (#5)		N/A (#6)		
8	13%	19	31%	19	31%	13	21%	0	0%	3	5%	Planning guidance provides sufficient information on how to adequately assess the feasibility of HN with CHP
0	0%	5	8%	8	13%	29	47%	18	29%	2	3%	Include a typical daily summer and winter thermal load profile
4	6%	28	45%	13	21%	12	19%	3	5%	2	3%	Finanical benifit from CHP electrcity export can always be expected
0	0%	2	3%	11	18%	38	61%	9	15%	2	3%	Capacity application for local gas and electrical infrastructure should be completed
0	0%	11	18%	22	35%	19	31%	7	11%	3	5%	HN with CHP is only selected when a development exceeds a minimum heat density (kWh/m2)
0	0%	1	2%	3	5%	34	55%	22	35%	2	3%	Accurate calculations of thermal distribution losses should be included
0	0%	3	5%	14	23%	32	52%	11	18%	2	3%	Life cycle costing compared to individual gas boilers should always be completed
0	0%	4	6%	11	18%	31	50%	14	23%	2	3%	Expected consumer heat tariff should be calculated
0	0%	5	8%	4	6%	33	53%	18	29%	2	3%	Final CHP size based on economical assessment of different CHP sizes

Q14 **To what extent have you used the following documents when considering the feasibility of a heat network with CHP for an Energy Strategy? Please select the relevant scale for each document below:**

Extensively Used (#1)		Commonly Used (#2)		Limited Used (#3)		Not Used (#4)		Don't Know (#5)		N/A (#6)		
20	32%	23	37%	10	16%	3	5%	1	2%	5	8%	The London Plan: Response to Climate Change
15	24%	20	32%	12	19%	9	15%	1	2%	5	8%	GLA: Sustainable Design and Construction SPG
9	15%	19	31%	19	31%	9	15%	1	2%	5	8%	GLA: District Heating Manual for London
22	35%	19	31%	10	16%	5	8%	1	2%	5	8%	GLA: Guidance on Preparing Energy Assessments
10	16%	21	34%	18	29%	8	13%	1	2%	4	6%	CIBSE: Heat Networks Code of Practice
5	8%	22	35%	21	34%	9	15%	1	2%	4	6%	CIBSE: AM12 Combined Heat & Power for Buildings
26	42%	20	32%	5	8%	5	8%	1	2%	5	8%	London Assembly: The London Heat Map online tool
2	3%	17	27%	20	32%	18	29%	1	2%	4	6%	CIBSE: Good Practice Guide 240: Community Heating

Q15 **In your experience, are any of the following aspects of an Energy Strategy changed post-planning during detailed design? Please select the relevant scale for each technology below:**

Never (#1)		Seldom (#2)		Occasionally (#3)		Often(#4)		Always (#5)		Don't Know (#6)		N/A (#7)		
2	3%	11	18%	16	26%	19	31%	7	11%	4	6%	3	5%	Thermal performance of building elements (U-Values)
3	5%	12	19%	17	27%	20	32%	4	6%	3	5%	3	5%	Designed air tightness
2	3%	10	16%	17	27%	22	35%	5	8%	3	5%	3	5%	Solar energy transmittance of glazing (G-Value)
2	3%	17	27%	29	47%	8	13%	1	2%	3	5%	2	3%	Ventilation strategy (MVHR, MEV, Passive Ventilation)
15	24%	23	37%	14	23%	3	5%	1	2%	3	5%	3	5%	Heat Network to Individual Gas Boilers
21	34%	24	39%	10	16%	0	0%	1	2%	3	5%	3	5%	Individual Boilers to a Heat Network
20	32%	24	39%	10	16%	2	3%	0	0%	4	6%	2	3%	Inclusion of CHP
13	21%	24	39%	13	21%	6	10%	0	0%	4	6%	2	3%	Exclusion of CHP
2	3%	8	13%	22	35%	18	29%	6	10%	3	5%	3	5%	CHP specified output (kW)
4	6%	30	48%	22	35%	1	2%	0	0%	3	5%	2	3%	Change of renewable technology type
2	3%	13	21%	22	35%	14	23%	6	10%	3	5%	2	3%	Specified output/size (kW/m2) of renewable technology

Q16 **In your experience, to what extent is the Energy Strategy document used during the different stages of the project? Please select the relevant scale for each project stage below:**

Never (#1)		Seldom (#2)		Occasionally (#3)		Often(#4)		Always (#5)		Don't Know (#6)		N/A (#7)		
5	8%	5	8%	16	26%	14	23%	13	21%	4	6%	5	8%	Stage 1 – Preparation and Brief including Pre-Application Discussions
1	2%	6	10%	7	11%	19	31%	22	35%	3	5%	4	6%	Stage 2 – Concept Design including Pre-Application Discussions
0	0%	3	5%	8	13%	12	19%	33	53%	3	5%	3	5%	Stage 3 – Developed Design including Planning Application
1	2%	3	5%	16	26%	15	24%	20	32%	5	8%	2	3%	Stage 4 – Technical Design
6	10%	18	29%	16	26%	7	11%	6	10%	7	11%	2	3%	Stage 5 – Construction including commissioning
19	31%	15	24%	15	24%	2	3%	3	5%	6	10%	2	3%	Stage 6 – Handover and Close Out
28	45%	16	26%	7	11%	0	0%	0	0%	9	15%	2	3%	Stage 7 – In Use

Q17 **In your experience, how involved is the original author/s of the Energy Strategy in the different stages of the project? Please select the relevant scale for each project stage below:**

Never (#1)		Seldom (#2)		Occasionally (#3)		Often(#4)		Always (#5)		Don't Know (#6)		N/A (#7)		
4	6%	12	19%	12	19%	19	31%	10	16%	2	3%	3	5%	Stage 1 – Preparation and Brief including Pre-Application Discussions
2	3%	6	10%	6	10%	21	34%	23	37%	2	3%	2	3%	Stage 2 – Concept Design including Pre-Application Discussions
0	0%	4	6%	12	19%	17	27%	25	40%	2	3%	2	3%	Stage 3 – Developed Design including Planning Application
3	5%	17	27%	12	19%	20	32%	5	8%	3	5%	2	3%	Stage 4 – Technical Design
13	21%	23	37%	12	19%	6	10%	2	3%	4	6%	2	3%	Stage 5 – Construction including commissioning
24	39%	18	29%	11	18%	2	3%	1	2%	4	6%	2	3%	Stage 6 – Handover and Close Out
35	56%	16	26%	3	5%	0	0%	0	0%	5	8%	3	5%	Stage 7 – In Use

Q18 **Considering the following statements, which best reflects your opinion/s on the energy performance gap in new developments? Please select the relevant scale for each statement below:**

Strongly Disagree (#1)		Disagree (#2)		Neither (#3)		Agree (#4)		Stronly Agree (#5)		N/A (#6)	
20	32%	28	45%	6	10%	1	2%	2	3%	5	The energy performance gap is not an issue in new developments
15	24%	27	44%	6	10%	10	16%	2	3%	2	The Energy Strategy document is suitable for comparison against actual in use energy consumption
12	19%	24	39%	16	26%	4	6%	3	5%	3	Feedback is given to policy makers on actual in use performance of LZC technologies
2	3%	8	13%	22	35%	17	27%	8	13%	3	Feedback to policy makers is ineffective regarding actual LZC technology performance
1	2%	5	8%	13	21%	30	48%	9	15%	4	Inadequate feasibility assessment during planning stage creates unachievable performance in practice
20	32%	10	16%	19	31%	7	11%	0	0%	6	Regulatory software for SAP Assessments is suitable for the assessment of LZC technologies

Q19 **In your opinion, based on your experience of Heat Network with CHP systems, is there an energy performance gap between the planning stage Energy Strategy and actual performance in practice?**

Lower than predicted (#1)		Approximately the same as predicted (#2)		Higher than predicted (#3)		Don't Know (#4)		N/A (#5)		
2	3%	6	10%	34	55%	17	27%	3	5%	Distribution heat losses
3	5%	6	10%	27	44%	22	35%	3	5%	Pumping energy consumption
20	32%	23	37%	2	3%	14	23%	3	5%	Efficiency of heat generating plant
21	34%	13	21%	11	18%	14	23%	3	5%	Consumers space and hot water heating requirements
37	60%	5	8%	3	5%	14	23%	3	5%	Savings in CO2 emissions