Department of Mechanical and Aerospace Engineering

Viability Analysis for District Energy Network: University of Strathclyde - John Anderson Campus

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Copyright Declaration

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Signed: Iain Stuart MacFadyen Date: 03/09/13

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Abstract

This study has assessed the viability of a proposed district energy network for the University of Strathclyde John Anderson campus. The assessment process included the comparison of the heat and power demand for multiple site variations, the analysis of possible waste heat storage for peak heat demand load shifting in the system and the use of waste heat for cooling through absorption chilling.

The main objective of this was study was to facilitate better-informed decisions for the project stakeholders with regard to the final energy network design. This was to be provided through conclusions drawn from a more detailed system analysis than has previously been undertaken, focussing on the use of metered rather than generic or simulated data.

This was achieved through analysis of the heat and power demand for the site using monthly and half-hourly metered data. The heat and power demand were both divided into a set of phased expansion stages to allow accurate comparison of heat to power for each potential combination and the identification of the best matched. The potential surplus or deficit of waste heat was calculated for each phase as the difference between daily demand and availability; the energy balance in the storage vessel was adjusted accordingly for the additional heat stored or required at each time step to identify which system combinations were sustainable. The cooling load as heat equivalent was calculated for each phase and the initial heat to power analysis re-evaluated to assess its viability.

The best matched system was identified to be the system combination with the maximum electrical generation with waste heat storage and a district heating network encompassing the Island Zone, Business Zone and Sports Centre. Cooling through absorption chillers was not found to be a viable option.

This identification of this stage as the most appropriate implies that previous analysis, which had suggested that expansion of the district heating system was viable past this point, may be flawed or inaccurate.

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Nomenclature

BRUKL:	Building Regulation UK part L
CCHP:	Combined Cooling Heat and Power
CHP:	Combined Heat and Power
COP:	Coefficient of Performance
EPC:	Energy Performance Certificate
HPR:	Heat to Power Ratio
kWh:	Kilowatt Hour
MWh:	Megawatt Hour
SBS:	Strathclyde Business School
SWD:	Sir William Duncan Building

1 Introduction

The University of Strathclyde is currently in the process of assessing the potential benefits that could be achieved through the installation of a CHP based district energy network on their John Anderson campus in the city centre of Glasgow. The proposed scheme would initially be operated as a localised installation with the potential for expansion into a much larger Glasgow wide scheme in the future.

There have already been several preliminary reports commissioned through Buro Happold, The Campbell Palmer Partnership, ATKINS and ARUP, with these initial evaluations indicating that there is definitely the potential for such a system to operate sustainably on the John Anderson campus site. However, the analysis undertaken for each of these commissioned reports has been based upon fairly high-level demand data for the campus; as such it is the intention of this study to assess the viability of the proposed campus energy network to a greater degree of accuracy than has previously been achieved.

The main goal of this thesis is therefore to assess the potential for the proposed energy network through the application of more accurate demand analysis than has been undertaken previously, with the purpose providing project stakeholders with more robust conclusions regarding the viability of the system. There are also several prospective aspects of the system design that have yet to be investigated and as such, if the scope of the study allows, concepts such as peak heat demand shifting and the use of waste heat for cooling will also be included in this analysis.

Achieving these goals will result in a position where viable advice regarding the design and operation of the system can be presented through the conclusions, leading to more informed decisions being made regarding the energy network proposal and consequently a more appropriate final system installed on the John Anderson campus.

1.1 Project Development

It must be said from the start that the basis for the generation and development of the proposed energy network project is the commitment of the University of Strathclyde to improving the energy efficiency and carbon footprint of their estate. While there are undoubtedly potential financial benefits to be achieved through the proposal, the origins of the project are firmly grounded in this determination to increase energy efficiency and reduce emissions from the John Anderson campus.

A complete breakdown of the development process for this project is not possible due to the commercially sensitive nature of the on-going project and the commissioned works involved. Rather this section aims to present a brief summary of the projects development up to this point, outlining the key steps to allow a limited structure of the proposal to be created.

According to the material made available for this study, the first development in the generation of the energy network proposal as it currently stands was a feasibility study prepared by Buro Happold, assessing the potential for a University of Strathclyde District Energy Scheme and commissioned in May 2007. This report was not made available, however the results of this initial study must have been promising as a further feasibility study was commissioned through the Campbell Palmer Partnership in June 2007.

This second study was prepared as a Carbon Management and Energy Efficiency Report for the University of Strathclyde Island Zone. This report (Palmer & Tamburrini, 2007) assessed the feasibility of the energy network from a practical perspective, looking at the existing systems in the four buildings that make up the Island Zone (The Royal College, James Weir, Thomas Graham and the Students Union) and how these could be potentially developed further.

From here the project development took an unusual turn and was included in more expansive plan than had been originally envisioned. With the announcement in November 2007 that Glasgow would be the host city for the 2014 Commonwealth

Games, several citywide improvement projects started gathering momentum, one of which was the Sustainable Glasgow Project (Sustainable Glasgow, 2013). These developments among others lead to the inclusion of the John Anderson site in an initial scoping study for Glasgow City Centre North Combined Heat & Power and District Heating, commissioned through ATKINS in May 2011.

This study (ATKINS, 2011) broadly assessed the potential for a large scale district heating network across various sites in the North of Glasgow, of which the University of Strathclyde – John Anderson campus was one. The report was then followed by a second, more detailed feasibility study commissioned through ARUP in May 2012. This second study (ARUP, 2012) took the broad assessment of the initial scoping study one step further, analysing the heat and power demands for each of the sites involved on a monthly basis to more accurately assess the project viability.

At this stage the development process took another turn, altering in scope once again but on this occasion returning more towards what was originally envisaged. While still maintaining a key role in the Sustainable Glasgow project, The University of Strathclyde was granted Stage 1 approval for a monetary grant to assist in the development of an Energy Centre on the Campus. This has since developed further into a more expansive Stage 2 approval, the details of which are currently being assessed by the stakeholders of the energy network project.

At the time of writing this remained the situation regarding the proposed energy network for the University of Strathclyde – John Anderson Campus. The project is clearly at a critical stage and as such it is the primary goal of this study allow more informed decisions to be made.

1.2 Literature Review

This is section aims to define and explore the concept of a district energy network through an overview of relevant literature, official documentation and related works; including a brief historical outline of its development in the UK, how the technology is developing to become a more viable option to meet energy demand and a review of other documented work in this area.

To clearly define the concept of a district energy network it is best to initially break it down to its most basic and then build up the definition from this foundation. At the most elementary level, the modern built environment has two main energy requirements: Electricity and Heat (CIBSE, 2006). It could be argued that in some instances cooling is also a critical requirement although, as this demand can be met by both electricity and heat energy, it cannot be defined as such. The traditional methods used to supply these energy needs have typically revolved around the generation of electrical power at a central or satellite location, which then meets the energy demand through a distribution grid, while heat has normally been generated at the site of the demand itself. This form of energy supply and demand matching has been applied around the world since the concept of electrical power use took hold around the start of the 19th century.

With this in mind, a district energy network is a relatively simple concept in that seeks to meet both of these main energy requirements. There are two key components to a district energy system as defined in this report, these being the supply of electricity through a grid network in combination with a district heating and/or district-cooling scheme to meet the energy demands of multiple sites simultaneously. As the provision of electricity through a grid network is typically already the established form energy supply to a site, the break from tradition for the district energy network comes though the implementation of district heating.

This is not to say that district heating is in any way a new technology, with the implementation of district heating in one form or another traceable back to the Roman Empire; although, the first recorded instance of what could be interpreted as the modern incarnation of district heating appears to be the significantly more recent application of an “experimental system” by a Mr Holly in New York circa 1887 (Turpin, 1966). The basic principle of a modern district heating network can be seen outlined in Figure 1:1 below.

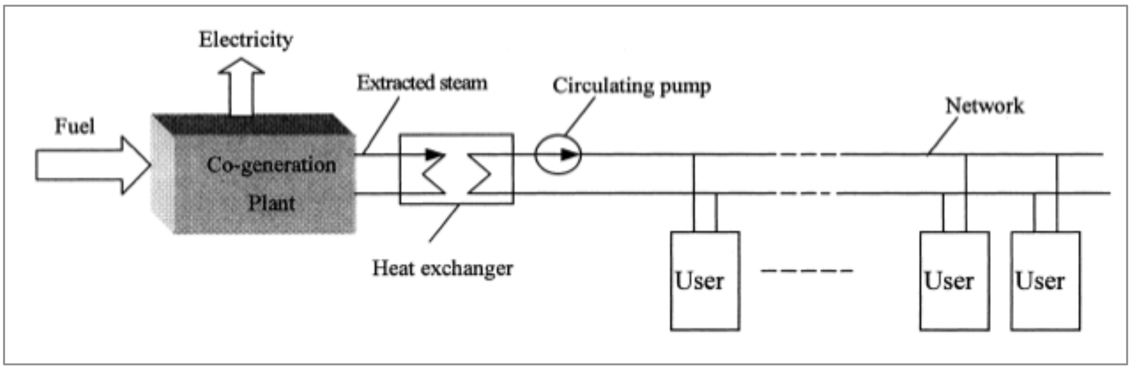

Figure 1:1 – Basic Principle of District Heating (Lin et al., 2001)

The diagram shown above in Figure 1:1 illustrates the basic operating principle of a district energy network in that, rather than the more traditional method in which heat is generated at the location of demand, heat demand is met by a central heat generating unit. Although the generation unit in Figure 1:1 is labelled as a co-generation plant, in principle a district heating scheme can be based upon any reliable source of waste heat such a power station generator or chemical process plant (Harvey, 2006); in locations where it is possible to do so, naturally occurring geothermal power can also be used as a source of energy for district heating.

Iceland in particular has had much success in the installation and use of district heating from geothermal sources, an image of the district heating network used to supply the heat for the Icelandic capital Reykjavik can be seen below in Figure 1:2.

Figure 1:2 - Geothermal District Heating Network for Reykjavik, Iceland[1]

As stated above, district heating networks in this form are an established technology and have been around for a long time. These networks have been widely utilised in many countries across the European continent in countries such as Germany, France, Russia, Poland and many others including a high installation rate in most Scandinavian countries; two particular examples of the prevalent use of district heating in Europe are the Vatican City, where heat is provided solely from a district heating network (Turpin, 1966), and the old USSR where "more than three quarters of heat demand" (Economic Commission for Europe, 1984, p.166) was met by centralised heat sources. However, this has not traditionally been the case in the UK.

There were a few examples of early district heating schemes in the UK prior to World War 2, notably in Manchester and Dundee (Turpin, 1966), although there appears to be very little other documented interest in the technology. This could primarily be attributed to political and economic reasons in the UK at the time, where "Prior to

[1] © Iain MacFadyen 2011

1939 coal was cheat and plentiful… and little attention was paid to environmental and air pollution" (MacKenzie-Kennedy, 1979). This limited application of district heating in the UK continued for some time after the war despite the multitude of development opportunities for such installations available the post-war Britain (Turpin, 1966).

While other countries across Europe continued the development an installation of district heating technology, with examples across Scandinavia in particular expanding rapidly through the 1950s and 60s (Rimmen, 1979) (Economic Commission for Europe, 1984), there was comparatively little serious development of district heating systems in the UK. This could possibly due to the oil and gas boom experienced by the UK through this time period; while other countries in Europe and Scandinavia were developing reliable district networks the overabundance of fossil fuels in the UK may have made efficient energy distribution less of a priority concern for the government at that time (MacKenzie-Kennedy, 1979).

It must be said however that there were some district heating development in the UK through this period. Some, such as the systems installed in Bretton Township (MacKenzie-Kennedy, 1979), Nottingham (Rowe, 1979) and Sheffield (MacKenzie-Kennedy, 1979) proved to be relatively successful although many early schemes also proved to be financially unsustainable due to a lack of experience with system operation and design (Turpin, 1966).

This improving but still relatively lacklustre approach to the implementation of district heating was to change in the 1970s however, with the fuel crisis experienced in 1973. This abrupt awakening could be perceived as a turning point in energy management in the UK. The sudden unavoidable truth of the "growing scarcity and rising cost of convenience fuels" (Diamant & Kut, 1981, p.vii) altering the governments approach to the application of resources and energy use and turning its attention more towards the achievement of more optimum efficiencies.

Up until recently this has essentially been the development path of district heating within the UK, with the high initial installation cost of the system possible holding back developers that are not guaranteed to see any adequate financial return for this primary expenditure (Harvey, 2006). The same scenario has not played out across the rest of continental Europe however, as shown below in Figure 1:2.

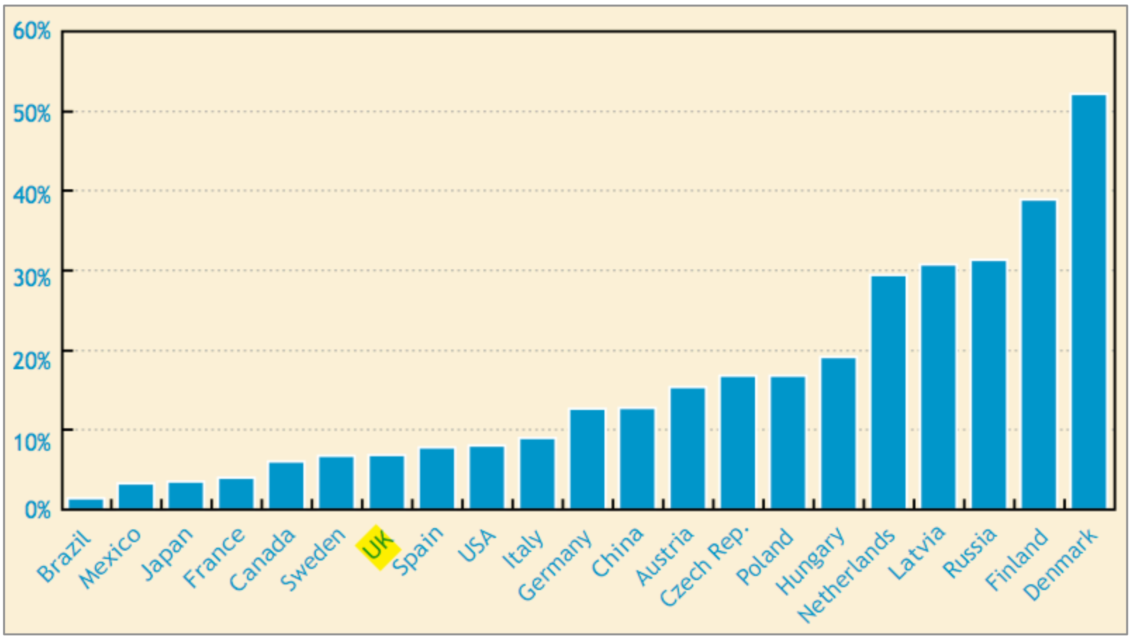

Figure 1:3 – Share of National Power Production met by CHP (Kerr, 2009)

Figure 1:3 above, accurate as of 2008, illustrates the vast divide between the UK and other countries, both in Europe and on a global scale, in the implementation of district heating technology. The scale of the district heating installations in Finland and Denmark are clearly world leading and highlight the dedication to energy integration and efficiency in these societies. One thing that is made abundantly clear in Figure 1:3 is that there is obviously room for improvement in the UK's approach to energy management and district heating in particular.

One key factor regarding the strong development of district heating schemes in many of the countries in which the technology is so prominent, aside from their typically hash winters and high overall heat demand, is that in many cases the development was primarily government led (Economic Commission for Europe, 1984) (Rolfsman, 2004). As stated above, the development of such extensive and costly district heating networks is unlikely to be undertaken without adequate financial reward or penalties imposed.

This has likely been the case in the UK although recent policy changes appear to be tackling this issue directly. Schemes such as the Renewable Heating Incentive (Department of Energy and Climate Change, 2013) and the proposed Carbon Tax (HMRC, 2013) in particular are making technologies such as district heating much more viable. The Renewable Heating Incentive represents the potential reward, supporting non-domestic, renewable heat installations by offering tariff-based rewards per kilowatt hour (kWh) of heat generated. Alternatively, the Carbon Tax represents the potential penalty in the form of a tax applied to all fossil fuel based electricity generation. These schemes also promote a change in the way that designers in the UK approach district heating as a concept; breaking away from the more traditional installation of stand-alone schemes around large power stations and more towards the Scandinavian approach to energy integration, involving multiple smaller scale CHP installations linked into a greater district energy network (Peacock & Newborough, 2007).

Another example of policy reform driving change to the approach to energy management within the UK can be seen in the restructuring of the landfill tax in Scotland (HMRC, 2013); new amendments to require the separation of waste before disposal and for those businesses generating over 5kg of food waste per week to introduce food waste recycling of face financial penalty. This change in policy has been attributed as one of the key factors in the proposed development of a combined anaerobic digestion facility and district-heating network as part of the Sustainable Glasgow project (Sustainable Glasgow, 2013). Between these schemes and some others still in the pipeline, the government seems to be taking steps towards making low carbon technologies such as district heating a much more viable and attractive option in the UK.

With regard to the analysis undertaken for this work, there are many examples of varied studies into the optimum design and operation district energy networks. Some of these dating back to periods where the modern, large scale forms of district heating technology were still relatively unknown (Rowe, 1979) (Rimmen, 1979), but most based around the recent revival in interest and implementation of district heating as an efficient form of complete energy provision.

Many studies are particularly focussed on the investigation of the various fuel sources available for district heating systems, extending to detailed analysis of the potential emissions for each and how these can both be managed and reduced. The analysis undertaken in (Ghafghazi et al., 2012) represents an extensive evaluation of the processes involved in selecting the appropriate fuel source for a district energy system; highlighting the difficulties encountered with conflicting stakeholder priorities regarding the fuel choice and how to clearly evaluate the best choice for the system.

This highlights the multitude of factors that must be considered when approaching the design and construction of a district energy network, while can initially seem to be a simple choice of efficient energy production there are various socio-economic and political aspects involved. This facet of district energy networking is touched on briefly in (Marecki, 1988, pp.140-64), which outlines the challenges and criteria required to accurately assess the combined cost of production, while the more specific socio-economic drivers involved with the implementation of district energy networks are assessed by (Madlener & Bachhiesl, 2007). This second article details the case study of the largest biomass cogeneration plant in Austria, supplying both heat and power the Austrian capital Vienna, and the challenges overcome achieve this installation in the one of Europe's largest and most traditional urban centres.

These concepts are explored with a more technical regard in (Burer et al., 2003), which evaluates the optimisation of both design and operation of a district energy network with regard to both cost and CO_2 emissions. The analysis undertaken in (Burer et al., 2003) is focussed more on what it defines as "thermo-economic" modelling of the network, assessing viability from a more financial rather than purely energy based perspective. The work does however also explore the requirement for efficient heat recovery in such a system as well as investigating the use of heat to power ratios (HPR) in the analytical process and the implementation of absorption chilling from waste heat, all of which are relevant to the work carried out in this thesis.

The application of HPRs in the analysis of district energy networks is also supported by the work of (Cardona et al., 2006), in which the difficulties that arise from the need to overcome the typically low HPR present in the built environment are evaluated. The article explores how this is best simulated for analysis through calculation and demand profile comparison; a process also applied in the study of a CHP in Sweden in (Bjorklund et al., 2001).

An alternative analytical method also widely supported is the direct analysis of the efficiency for the generating plant for the district energy network. This methodology is applied to good effect in (Rosen et al., 2005), which quantifies and evaluates both the energy and exergy of the proposed system. This process involves the calculation of the total percentage efficiency of the system through analysis of the exergy, rather than load-demand matching to gain the HPR. While the article does explore the application of both district heating and cooling, the analysis was developed as an extension of an original engineering report; this original report was based upon energy demand matching and HPR analysis, suggesting that the work of (Rosen et al., 2005) is a potentially worthwhile expansion of that initial system assessment.

The forms of comparative load-demand matching and HPR analysis performed to achieve that original engineering report is more in line with the analysis to be undertaken in this thesis. One form of this more high-level methodology is evaluated in (Dotzauer, 2002), which focuses on the development of a relatively simple load prediction model to standardise optimisation routines for energy networks. This process relied heavily on heat load forecasting to determine a prediction for heat demand; as such the use of demand profiling was critical in this methodology, specifically referring to the social behaviour, represented in demand profiles, as having the greatest influence one demand (Dotzauer, 2002).

The specific issues encountered in profiling energy demand over time, down to over even a 24-hour period are evaluated by (Rolfsman, 2004), through the investigation of heat storage applicability in a CHP based energy network. Although the purpose of this article is more focussed on the integration of CHP plants into the power market, is also quantifies the challenges faced through the selection of appropriate time steps the averaging of data in the analysis of an energy network.

Also relevant to the anticipated analytical method to be applied in this thesis is the assessment and use of various energy network simulation methods performed by (Benonysson et al., 1995). This article investigates how to achieve the most appropriate supply temperature through simulation and defines several assumptions that make the analysis possible; these include the assumption of the system efficiency as a constant value and ignorance of the start-stop nature of a typical CHP system. This simplification of the analytical method is supported by (Dotzauer, 2002), which states that, “when measured data is lacking, and due to natural uncertainties, simple models may give as good predictions as complex. This is also the experience from the applications analysed in this paper”.

There are also several examples of some of the more specific analysis that can be undertaken in the assessment of a district energy network. The benefits of implementing heat storage in combination with a district-heating network has been touched upon by several articles mentioned above; however, a clearer assessment of the overall benefits that can be achieved through this combination are outlined in (Gustafsson & Karlsson, 1992). This article compares the overall heat produced by a CHP unit with the heat demand of the system and evaluates the potential for heat storage. The flow diagram for the system investigated in the article can be seen below in Figure 1:4.

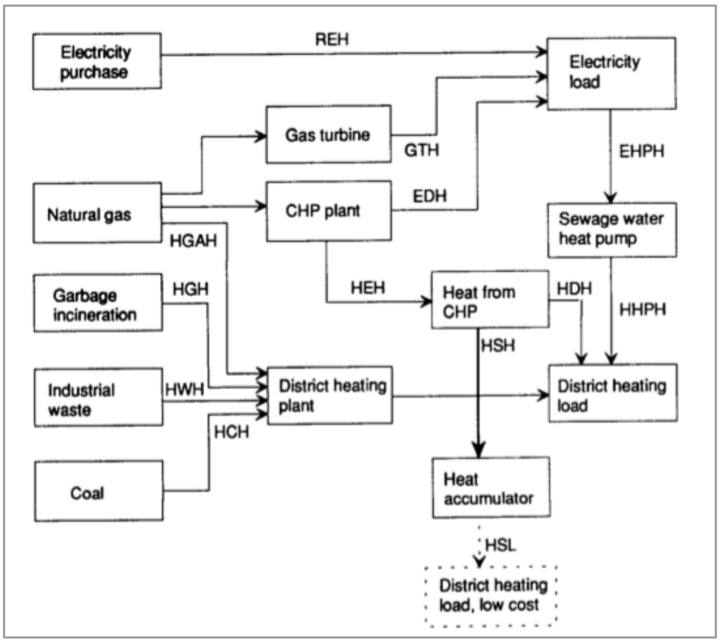

Figure 1:4 – Flow Diagram for District Energy Network with Heat Storage (Gustafsson & Karlsson, 1992)

The system shown in Figure 1:4 is clearly a completely integrated district energy network, the section of the diagram specific to the work in this thesis focussed on the interaction between the CHP plant, the District Heating Load and the Heat Accumulator. This system was shown to beneficial in (Gustafsson & Karlsson, 1992), where the additional waste heat was used to meet peak heat demand when demand rose above that which was available. The use of heat storage in combination with a district energy network is also advocated in (Ter-Gaszarian, 2011) and by (Tveit et al., 2009). The first of which explores and defines the application of energy storage in general to meet the incredible varied demand profiles of modern society, while the second article analyses the specific operation of long-term thermal storage for CHP plant in district heating networks.

Much the same as for heat storage; there is a lot of documented analysis for the potential of district cooling and the use of absorption or adsorption chillers. The difference between the latter two systems is best defined by (Harvey, 2006), as shown in Figure 1:5 below.

> "The process of attracting and holding another substance is called absorption if a chemical change occurs (as in when table salt absorbs water and liquefies) and is called adsorption when no chemical change takes place (as in when silica gel desiccant adsorbs water – the desiccant does not change except from the addition of the weight of the water)"
>
> (Harvey, 2006, p.261)

Figure 1:5 – Absorption/Adsorption Differential

The clearest example of the evaluation of an integrated cooling and heating energy network was found in the work by (Wu & Wang, 2006). This article detailed multiple analytical methods that could be applied to various energy generation combinations that could be applied to form a combined cooling, heating and power energy network (CCHP). The use of absorption chillers was advised as the most appropriate cooling method for such an arrangement, typically best suited to large scale CCHP installations.

2 Project Outline

As stated in the introduction above, several preliminary reports have been produced which assess the viability of the campus energy network project and the findings so far have been very positive. It has been demonstrated that there is definitely the potential for a sustainable energy network installation on this site however the final design is still unclear with many options still being considered.

It is therefore the intention of this thesis to provide the stakeholders for energy network project with a clearer understanding of how the system could be best designed and operated through more a detailed analysis of the recorded energy demand for the site. This will include the investigation of some options for the proposal that, while they may have been considered, have not yet been examined in any great detail. This thesis also aims to demonstrate and assess the variations in the accuracy of energy analysis through alternate information sources such as monthly, daily and half hourly data with the purpose of allowing those commissioning any future analysis to make a more informed decisions regarding the cost to quality balance.

To date most of the reports commissioned have been based on template or generic demand data[2]; however, while this is a valid form of analysis at the preliminary stage of the deign process, more in depth assessment is required before a final design can be achieved. To attain this increased level of accuracy it is intended that wherever possible all calculations and analysis performed in this thesis will be carried out using real, metered data. The step from high-level generic to time stepped, metered data allows the actual performance of the system to be assessed rather than how the system is assumed or anticipated to perform.

In the project proposal (Drobot, 2013), which outlined the scope of the energy network project, the John Anderson campus was split into five distinct phases to represent potential, progressive stages of network expansion. These original phases, as seen below in Figure 2:1, represent a logical development of the energy network as a district heating scheme from the University Island Zone along Cathedral Street to include the

[2] (Palmer & Tamburrini, 2007) (ATKINS, 2011) (ARUP, 2012)

Business School Zone, the proposed Sports Centre, The HASS Zone and the Student Residences. Each of these zones is defined below in Table 2:1.

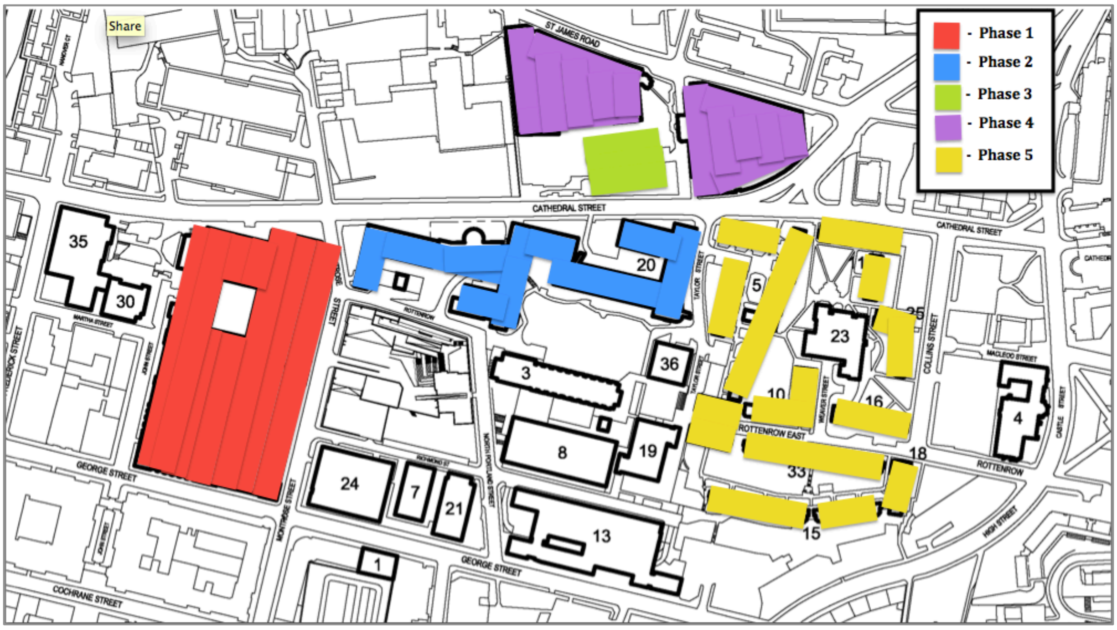

Figure 2:1 - Original Energy Network Phases

Table 2:1 - Initially Proposed Phases of Project Expansion

Initial Phases of Project Expansion		
1	**Island Zone**	Royal College Building
		James Weir Building
		Thomas Graham Building
		Students Union
2	**Business Zone**	Hamnett Wing
		Henry Dyer Building
		John Arbuthnott Bld Robertson Wing
		Sir William Duncan Building
		Stenhouse Building
		Strathclyde Business School
3	**Sports Centre**	Sports Centre
4	**HASS Zone**	Curran Building
		Lord Hope Building
		181 St James Road
5	**Residential Zone**	Student Residences

The analysis study has been based on an expanded version of these initial five phases to involve more of the campus, including the new Technology & Innovation Centre that is currently under construction. This the expanded network used for this project phases can be seen below in Figure 2:2.

Figure 2:2 - Extended Energy Network Phases

A full numbered map of the campus along with a complete breakdown of the extended network expansion Phases can be found in Appendix 1.

The incremental increase of each proposed Phase of expansion has been based on the original five zones. Each additional Phase represents the logical progression of network expansion up to and including the proposed Technology and Innovation Centre (TIC Building) at Phase 10. The progress begins with the inclusion of those buildings adjacent to the original five zones but not included in the proposal. This continues with buildings grouped according to their location and distance downhill from Cathedral Street. Phase 9 is the only exception to this rule, as the combination of the Graham Hills building and Barony Church is based upon their mutual electrical energy supply from the Graham Hills Substation as opposed to the Central Substation that supplies the rest of the campus.

Accordingly, the Staged expansion of the electrical energy network for this analysis begins with the Central Substation and expands to include the Sports Centre, the Graham Hills Substation and the TIC Building, in that order.

These ten phases for the proposed district heat network, in combination with the four stages of electrical expansion, will provide the basis of the analysis carried out in this report.

With regard to the data to be used in this analysis, four main sources of information and data were made available to this project: monthly electricity and gas consumption data for each building on campus, half-hourly electricity and gas demand for all available buildings on campus, Energy Performance Certificates (EPCs) for each building on campus where available and the previous analytical reports commissioned for the proposed energy network. With a project of this type, based almost entirely on data analysis, the validation and processing of the data to be used is critical to the project's success. The data validation process is most likely to apply to the monthly and half-hourly data sets as these will be used as the primary source of information for the project.

The manipulation for comparison of very large amounts of data in different formants and from different sources could also to some extent represent the greatest challenge faced in the project. As the bulk of the data is to be presented in an Excel spreadsheet format, and given the promiscuity and popularity of the program, it is likely that Excel will be used to process the bulk of the data.

2.1 Aims and Objectives

The primary objective of this thesis is to use real, metered data in the assessment of heat to power ratios and load demand matching on the Strathclyde University Campus to identify the most appropriate scale and combination of potential sites for the combined heat and power network currently under consideration. The assessment will include multiple campus building combinations and be carried out on a monthly, daily and half hourly basis. The analysis of the data over these three time frames will also allow the qualities and disadvantages of each to be clearly demonstrated. The impact of including the new Technology Innovation Centre (TIC Building) and potential new Sports Centre installation in the energy network will also be assessed.

The second objective of this thesis is to analyse the on campus potential for the use of possible waste heat from the energy network. This includes investigating the implementation of peak heat demand load shifting and the possible use of waste heat in either a district cooling system or alternate cooling mechanisms.

These aims and objectives have been laid out more clearly below:

1) Use real recorded demand data to assess and compare both heat to power ratios and load demands over the proposed network for monthly, daily and half-hourly timeframes:
    i) Identify the most appropriate network combination
    ii) Clearly illustrate the advantages and disadvantages for each timeframe
    iii) Assess the impact of the TIC building and Sports Centre on the network

2) Investigate the quantity of and possible uses for any waste heat that may be generated by the proposed network:
    i) Quantify waste heat for anticipated network combinations
    ii) Assess potential for demand load shifting
    iii) Examine use of excess heat for cooling purposes

2.2 Scope and Project Limitations

As with all studies of this type, the time frame applied resulted in some limitations to the analysis, defining either the breadth or depth of the analysis that can be undertaken. This is doubly true for a project of this nature, in which there are a great many facets of the proposed energy network that would present valuable and challenging work but could not all be achieved in the time frame. This section therefore aims to set out some of the degrees of limitation that have been applied to reduce the scope of the project into a more manageable subject for an MSc thesis.

It was decided that the inclusion of financial implications for each phase in the system, in addition to the energy analysis, would be too much analysis to achieve any robust conclusions for either and so would also be outwith the scope of this project.

For much the same reasons it was also decided that any form of cost benefit analysis would be outwith the scope of this project.

Due to the anticipated high workload for the analysis already planned, it was decided that the physical design of the system and any challenges faced by its installation would be too complex to achieve to a high enough standard and so these were deemed outwith the scope of this project.

Along with the physical design of the system, it was decided that the calculation and analysis of potential losses from the district heating or cooling system would be outwith the scope of this project; these transmission losses tend to be around 5-15% for a hot water system and 15-45% for steam (Harvey, 2006).

It was decided that the inclusion of individual system efficiencies would increase the complexity of the analysis to an extent that would limit the scope of other stages and so would also be outwith the scope of this project.

It was also decided to limit the analysis of the district heating scheme to the identification of network combinations in which the full heat demand has been met.

2.3 Justification of Goals

Overall, this project has been designed to be of benefit to the engineers and decision makers throughout the campus energy network design process. The results achieved through the various analytical aspects of this thesis should prove advantageous to these parties by improving on previous work, providing real comparative data and information regarding the site that was previously not available. By demonstrating the differences between different degrees of energy analysis this thesis shall also provide a clearer understanding of the quality of the results achieved in alternate reports and studies carried using this data.

The assessment of load demand matching and heat to power ratios, particularly with the inclusion of a variety of network options and the inclusion of metered data, should provide a picture of the potential system performance and the viability of possible energy network combinations; the accuracy of which should only be limited by the quality of the data provided.

Analysis of recorded monthly energy-use on an annual scale should allow an overall image to be generated of the large-scale load matching on the site. The investigation of the monthly demand data for the campus is the highest-level analysis to be carried out in this project, from which the broadest conclusions as to the potential for a CHP energy network system on the campus can be drawn. Looking at monthly demand data only allows for an initial impression of the load demand matching, as the nuances of hourly and daily demand are lost at this level. These limitations would seem to indicate that there is no place for this level of analysis in the load demand matching process; however the comparison of monthly demand totals allows the comparator to see clearly, through a relatively straight-forward process, high-level heat to power demand ratios for a system and so whether there is any real potential for the proposed CHP energy network. This primary analysis is the least time consuming, and therefore also the least costly, of the processes used in the demand assessment and will quickly highlight whether any further analysis of the site is worthwhile. As such, this process has already been carried out to varying degrees of accuracy in the reports previously commissioned with regard to the energy network project.

Further analysis using daily totals, created from summed half-hourly recorded data, provides a clearer view of heat to power ratios throughout the year. The investigation of the energy demand on a daily basis allows for a far clearer image of the relevant profiles to be created. Whereas the monthly demand data will provide a high-level profile of heat and power demand over the set period, assessment of daily demand allows the comparator to see possible weaknesses in the demand matching that are missed at the monthly level such as a disparity between the weekly and weekend demand. This level of analysis presents a greater challenge and is obviously far more time consuming than the monthly analysis, although the benefits of a much more detailed demand profile can certainly outweigh these drawbacks.

Even more detailed than using daily demand data, analysis of half-hourly demand data is the one of the most accurate depictions of actual energy use for a site available. In much the same way that daily demand data highlights demand differences overlooked in monthly analysis, half hourly demand data allows a true profile for the energy demands of a site. This accuracy comes at a cost however as the increased amount of data presents a greater challenge in both analysis and presentation, ultimately requiring proportionally more time and effort to process than the other forms of analysis.

That said, any accurate analysis of actual consumption data over these timeframes should lead to more educated design decisions being made with regard to the proposed energy network, with the option to undertake more specific analysis to validate any results if required. Any further load demand matching analysis would also be tasked and performed from a position of knowledge, with areas of interest already highlighted through this investigation.

The concept of heat load shifting has also been considered for the proposed campus energy network but as yet has not been investigated. The preliminary analysis carried out in this thesis should therefore provide a clearer understanding of the potential for heat storage and demand shifting in the energy network project. One aspect to be investigated in particular is the use of excess heat from the system to power absorption chillers in the network, thereby potentially reducing electrical demand and increasing overall efficiency through reducing waste heat.

2.4 Work Plan

This section of the report splits the work undertaken into three subdivisions, each representing one of the three main goals outlined in the section above, with the purpose of breaking down and setting out the approach to both data processing and analysis to be executed at each stage. The subheadings below will outlay the planned approach to the work processes required to achieve the desired goals, while the exact techniques and methodology applied in the analysis will be defined in the relevant chapters to follow.

2.4.1 Initial Data Processing

The first and most important step in any project involving numerical analysis is the assessment of the initial data quality and validity.

1. Validate the data sets to be used through numerical assessment and comparison with other data sources, this includes:

    a. Scouring the data sets for spikes, missing or erroneous data

    b. Ensuring sets of digitally and manually recorded data are in agreement

    c. Adequately overcoming any issues encountered while maintaining the integrity of the data sets

2. Clearly recording any assumptions or decisions made in the validation process

2.4.2 Load Demand Matching

This will be separated into three separate analysis based upon the three time frames of the data sets under investigation; however the process for each analysis will follow this same basic structure. The following represents the planned workflow for the load demand matching section of this analysis.

1. Collect and process the original demand data into a form suitable for analysis, this includes:

    a. Forming daily consumption data from the half-hourly data set

b. Precise generation and application of percentage demand profiles where required

c. Manipulating data sets for each timeframe into a form which allows accurate analysis, while retaining data quality

2. Detailed analysis of heat to power demand matching for the planned University of Strathclyde campus energy network, this includes:

   a. Investigating the demand load profiles for monthly, daily and half-hourly timeframes within an organised analysis framework

   b. Investigating the heat to power ratios for multiple iterations of the potential energy network

   c. Assessing the qualities and accuracy of the results achieved for each time step

3. Demonstrate a clear and well-justified conclusion for the ideal energy network arrangement from the results of the analysis

2.4.3 Potential Waste Heat Analysis

In this section, the results achieved in the primary stages of the assessment will dictate the direction and depth of further analysis into the waste heat aspect. This is simply due to the fact that any further analytical options will be limited by the levels of waste heat found in the primary analysis, just as in the case that if no potential for waste heat in the system is found then no further analysis will be required. In consideration of this factor, the latter stages of the workflow for this portion of the analysis are representative of the work to be undertaken, still dependent on the results of the initial assessment. The following represents the planned workflow for the potential waste heat analysis section of this report.

1. Gather and process the required demand data and process for the analysis, this includes:

    a. Collecting the half hourly heat and electrical demands for each site

    b. Processing this data into a form in which the waste heat created through electrical power generation can be compared to heat demand

2. Examine the level and variation of the heat energy available to the network and how this could be best used, this includes:

    a. Quantifying the excess or shortage of available heat energy on a monthly, daily and half-hourly basis

    b. Perform this analysis for multiple iterations of the potential energy network

    c. Assessing which of these phase combinations is the most viable

3. Analyse the results of this process to assess the most viable demand to be met by the energy network and the scope of any further analysis regarding waste heat from the system. This further analysis could include:

    a. Investigating the application of heat storage to effectively shift and meet peak heat demand

    b. Assessing the potential for use of excess heat for cooling purposes

4. Achieve clear and well-justified conclusions as to degrees of waste heat likely to be available from the energy network and the most appropriate application of this heat.

3 Data Processing

In this thesis, the work involved and the techniques applied in the data manipulation process, for both the assessment of data quality and the methodology applied to prepare the data for analysis, are very representative of the project as a whole. The majority of the analytical procedures undertaken in this project both originate and conclude with the collection and arrangement of the available data sets. This is first performed to assess both the data quality and feasibility of using each data set to achieve the desired goal, followed by the careful manipulation of the data in such a way that its original value is not lost, and lastly by arraying the collected data once more in a fashion that facilitates the desired analytical process. While the techniques used in the data analysis process are detailed in the Methodology chapter of this report, the following sections are dedicated to the primary assessment of the data quality along with the decisions and assumptions that were made through the development of this assessment.

As stated earlier in this report, for a project in which the outcome is based almost entirely on numerical data analysis, the data quality and validation is critical to the projects success and the value of the results it produces. It must be possible to repeat the given analysis and achieve identical results; as such, the source of the data used, the validity of this data and any assumptions made with regard to its application in the analytical process must be clearly stated.

This chapter has therefore been broken down into three sections to outline the data, define the validation processes used and any assumptions or decisions made with regard to their application; the methods applied to manipulate the necessary data into a form that could be analysed are covered in the following methodology section.

3.1 Data Availability

The primary source of data used for analysis in this thesis was the University of Strathclyde's Estates Service department. Through which both gas and electrical demand data were provided for the campus on a monthly and half hourly basis along with all the available Energy Performance Certificates (EPCs) for the buildings on campus, three previously commissioned reports related to on the energy network and the secondary proposal document for the energy network project.

The monthly data available for the campus was sourced from manually recorded demand data, taken from meters located around the campus that are read on a monthly basis. This data is therefore representative of the electrical and gas demand for each building on campus with an active meter. Monthly demand data for the campus was made available from August 2010 up to June 2013.

Conversely, the half-hourly data was sourced from a digitally recorded demand data set, collected through an automated system every half-hour. The half-hourly electrical data is recorded for each substation that supplies the university rather than for each building. Half-hourly electrical demand data for the campus was made available from the 1st of August 2010 up to the 30th of June 2013. The half-hourly gas data records the demand for each building, although due to the recent installation of this system for the gas network the data set is less extensive than the others. Half-hourly gas demand data for the campus was made available from the 4th of September 2012 up to the 30th of June 2013.

The collected EPC data set included the performance certificates, recommendations report and energy profiles for each building. EPC data was made available for 35 buildings in total, 23 of which were within the scope of this thesis. The pre-construction BRUKL (Building Regulation UK part L) document for the new Technology Innovation Centre currently being built was also made available.

The three previously commissioned reports represent initial scoping studies and analysis carried out into the energy network project at various stages of its development from 2011 and 2012. These reports, prepared by ARUP, ATKINS and the David Palmer Partnership respectfully, provided a clear overview of the energy network project and were used for validation of the investigation proposed in this thesis.

The proposal document, prepared by the University itself, outlined the energy network project in a series of progressive stages; each stage an incremental increase in the scale of the network proposed, in keeping with the layout and infrastructure of the campus itself. The proposal document also contained summarised demand data for the campus and illustrated the use of an analysis framework that was applied to clearly demonstrate the comparative energy demands on the site.

These data sources were used as the foundation of the analysis carried out in this thesis. Before using any data however, the quality of the information had to be assessed to ensure the results of the analysis would be valid. The process used to assess and validate the data is outlined in the sections below.

3.2 Data Validation

The application of a given data set for analytical purposes of any kind begins with an assessment of the data quality and the validation of the contents against a known source. This process helps to ensure that any results achieved in the proposed analysis are both valid and comparable with current and future data relating to the system in question. This section is split into two sections, setting out the methods applied followed by the resulting decisions and assumptions made.

3.2.1 Data Analysis

This section outlines processes applied to the each data set to assess its quality and the manipulation of the data for later comparison. The quality of each data set was quantified by scouring the data for three main issues: data spikes, missing data and erroneous data. It is important to note that these processes can only identify potential data issues, further manual assessment of each data set is required to ensure the Both the methods applied and results of these analyses are shown below.

- Monthly Data Quality:

To assess the monthly data the demand for each building was averaged and the maximum value for that building found. The percentage difference for all the buildings was then averaged for comparison with the individual percentage. The difference between the two figures would therefore aid in the identification of any potential data spikes by highlighting any data set with a higher than average divergence between the maximum and average demand.

The each data set was then filtered (Excel data processing technique, defined in section 4.1.3 below) to represent only those rows with blank cells, thereby identifying any missing data present in the data set. To find any erroneous or patterned data the whole monthly data set was entered into a time variable line graph. This allows any patterns or diversions from the anticipated form to be highlighted for further analysis. The results of this assessment can be seen below in Table 3:1.

Table 3:1 - Quality Assessment: Monthly Data Sets

Data Set	Building	Issue Identified
Gas (Monthly)	Lord Hope	Missing Data : From June 2011 to June 2012.
Gas (Monthly)	Sports Centre & TIC Building	No Data Available
Electrical (Monthly)	Hamnett Wing	Missing Data : from August 2010 - June 2011 and August - September 2011
Electrical (Monthly)	Hamnett Wing	Data Spike : July 2011 is around 10x greater than all others for this building
Electrical (Monthly)	Sports Centre & TIC Building	No Data Available
Electrical (Monthly)	Thomas Graham	Missing data : From March - June 2013

- Half-hourly Data Quality:

Due to the difference in the presentation of the half-hourly data sets – Electrical data was presented in one column and split between the substations, while gas data was presented in a matrix format and split between each building - the quality assessment required more data processing to achieve the desired analysis; however, this process is described in detail in section 4.1.3. With the half-hourly data for both electrical and gas demand arrayed into format of one column per demand site, the analysis process is much the same as defined above for assessment of monthly data.

The demand for each site was averaged and the maximum found, with the difference between the individual result and the individual average indicating a potential data spike. The scale of the half hourly data set was so large that an IF function (Excel data processing technique, defined in section 4.2.4 below) was applied to identify those with divergences of varying degrees. Blank cells and erroneous data were identified once again through use of data filtering and graphical representation. The results of this assessment are shown below in Table 3:2.

Table 3:2 - Quality Assessment: Half-hourly Data Sets

Data Set	Building	Issue Identified
Gas (Half-hourly)	Architecture & James Weir	No Data Available
Gas (Half-hourly)	All	Erroneous Data : Staggered start date across data set
Gas (Half-hourly)	All	Erroneous Data : Given Daily totals in data set do not match summed total of Half-hourly demand
Gas (Half-hourly)	Garnett Hall (21836700)	Erroneous Data : Zero reading from 30/10/12 to 17/02/13
Gas (Half-hourly)	Garnett Hall (21836700)	Missing Data : [18/02/13]
Gas (Half-hourly)	Graham Hills (14468504)	Erroneous Data : Zero reading from 11/06/13 - 30/06/13
Gas (Half-hourly)	James Blythe Court (14469102)	Erroneous Data : MPRN actually represents Chancellors Hall
Gas (Half-hourly)	John Anderson (14468605)	Missing Data : [14/01/13], [12/04/13] & [15/05/13]
Gas (Half-hourly)	John Anderson (14468605)	Erroneous Data : Zero reading [11/01/13 - 28/01/13], [06/03/13 - 11/04/13] and [07/06/13 - 30/06/13]
Gas (Half-hourly)	John Anderson (14468605)	Data Spike : 14:00 on 17/04/13 - spike of 5592 kWh
Gas (Half-hourly)	Students Union (15598410)	Missing data : [02/05/13]
Gas (Half-hourly)	Thomas Graham (15598006)	Missing Data : From [04/01/13 - 27/01/13]
Electrical (Half-hourly)	N/A	No issues Found

The numbers shown after the name of the buildings for the Gas data set in Table 3:2 above represent the MPR (Meter Point Reference) for that meter. This is shown to remove any possible confusion as to the meter referred to in the table as some buildings on the campus have more than one meter installed.

- Data Validation

The monthly and half-hourly data sets were validated against one another. The monthly electrical data was summed according to the substation supplying each building to facilitate ease of comparison with the half-hourly data set; the results for this division of the campus according to electrical substation can be found in Appendix 2. The gas data sets for both the monthly and half-hourly time frames were summed according to the relative phase in the network expansion, as described above in section 2, with half-hourly gas demand converted into its equivalent monthly total. The results of the gas data set comparison can be seen in Table 3:3 below, with the results of the electrical data set comparison over the same time shown in Table 3:4; the full electrical data set validation table can be seen in Appendix 3.

Table 3:3 - Gas Data Set Validation

Percentage of Monthly Recorded Demand met by Half-Hourly Data-set								
Month	Phase 1	Phase 2	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9
Sep 2012	24%	32%	0%	71%	0%	45%	0%	22%
Oct 2012	24%	38%	0%	78%	0%	45%	0%	28%
Nov 2012	26%	35%	0%	70%	0%	39%	0%	21%
Dec 2012	40%	48%	41%	84%	37%	45%	25%	46%
Jan 2013	113%	61%	112%	95%	142%	60%	77%	96%
Feb 2013	106%	66%	100%	98%	127%	45%	76%	114%
Mar 2013	111%	76%	117%	109%	146%	47%	79%	109%
Apr 2013	95%	86%	88%	83%	121%	59%	65%	90%
May 2013	98%	92%	94%	87%	122%	93%	65%	94%
Jun 2013	105%	53%	108%	104%	142%	144%	105%	124%

The results shown in Table 3:3 (and Table 3:4 below) illustrate the percentage of the figure recorded manually in the monthly data set that is achieved by the summed total of the half-hourly data for that month. For example: Table 3:3 shows that in September

2012 only 24% of the manually recorded monthly gas demand for Phase 1 was concurrently recorded in the half-hourly data set for that month, 74% less than the manual data; while in February 2013, 106% of the monthly gas demand for Phase 1 was recorded by the gas half-hourly data set, 6% more than in the manual data. A value of 100% would indicate that the demand recorded through both manual and digital means were equal for that month, with 0% indicating a missing value in the half-hourly data set.

Table 3:4 - Electrical Data Set Validation

	Monthly Reading		Monthly (HH) Reading		% Difference	
	Central Total	GH Total	Central Total	GH Total	Central	GH
SEP 2012	2208881	278862	2277408	289323	103%	104%
OCT 2012	2548063	371159	2596311	372949	102%	100%
NOV 2012	2755480	404984	2653320	393543	96%	97%
DEC 2012	2395365	375614	2520692	376639	105%	100%
JAN 2013	2623284	394690	2774682	406675	106%	103%
FEB 2013	2580224	386796	2620549	375029	102%	97%
MAR 2013	2450340	389761	2844821	417938	116%	107%
APR 2013	2292760	355321	2655434	361237	116%	102%
MAY 2013	2341206	423811	2596922	360138	111%	85%
JUN 2013	2013328	194721	2350337	279777	117%	144%

Possible causes of any substantial divergences identified in the analysis were subsequently either determined through further manual analysis or sought from the estates services; the results of this further investigation and the subsequent decisions made are defined in the following section.

For the purposes of the analysis undertaken in this thesis it was decided that both the commissioned reports and proposal document did not require validation or quality analysis. Any data extracted from these documents was done so on the basis of recommendation only and stated in the relevant assumptions for that section.

3.3 Data Validation Results

The results of the data quality and validation assessment outlined above identified several issues with the given data sets that had to be addressed before the analysis could progress. The three primary concerns identified were: the disparity between the daily totals given in the half-hourly data set when compared the calculated sum of the demand for that day, the low validity of the half-hourly gas data for the first four months that it is available, and the lack of half-hourly gas demand data available for the Architecture and James Weir buildings as well as the complete lack of any demand data at all for the Sports Centre & TIC building.

The first of these, the variation between given and calculated daily demand, presented the most serious questions regarding the quality of the half-hourly gas data set but also worked out to be the most straight-forward data issue to resolve. The potential problem was brought to the attention of the Estates Services department and a recalibrated version of the half-hourly data set was provided, without the disparity between daily demands, which completely resolved the highlighted quality issues.

Regarding the second of these key concerns, the staggered nature of the half-hourly demand availability was easily explainable through the relatively recent installation of the digital meters on the campus; however, even with the source of the issue identified, it was clear that the severe disparity in the half-hourly gas demand data quality would be an issue for the purposes analysis.

To resolve this situation it was decided that, while the monthly data analysis for the campus would extend to a full year, the half hourly demand analysis would be limited to the data available from the 19^{th} of December. This date was chosen due to the availability of data for all but one of the buildings on this date, as illustrated in Table 3:3.

With regard to the third of these primary concerns, at the time of this report both the proposed Sports Centre and TIC Building had not yet been built, let alone had their energy use monitored. However, these buildings represent a substantial proportion of the anticipated future energy requirements for the campus network and as such it was thought that their absence from this analysis would severely limit its value. It was therefore decided to include these buildings through the application of percentage demand profiles. This process would apply the anticipated electrical load to the Central

Substation demand profile the heat demand of the Sir William Duncan and Curran buildings for the TIC building and Sports Centre respectfully.

A more detailed outline of all the decisions made with regard to data quality and validation can be found in Appendix 4 below. Other important assumptions and decisions made to facilitate the analysis outwith the application of the data sets are outlined in the section below.

3.3.1 Assumptions & Decisions Made

This section outlines the key assumptions and decisions that were made to facilitate the analysis and keep the project within its original scope. The statements listed below are therefore necessary to understand the scope and limitations of the following analysis. Justification for the assumptions stated here can be found in Appendix 4.

- The heat to power ratio of the energy network system was assumed to be 1:1 to represent electric to heat power output in the following analysis.

- The efficiency of all local heating systems was assumed to be 100%, allowing the gas demand to directly represent the heat demand. Gas demand from catering and lab applications was removed where ever possible.

- The phased progression of the network development was assumed as was set out in the project outline above and further defined in Appendix 1.

- In the absence of demand profiles or static annual loading data it was assumed that cooling profiles used in the analysis, generated through use of the building simulation software Esp-r, would be appropriate for the scope of the analysis.

- CIBSE standards were assumed for all applied gains in the Esp-r model.

- The Absorption chiller used in the following analysis was assumed to be a Lithium Bromide Absorption unit with a coefficient of performance of 0.7.

- Dimensions for the thermal storage vessel used in the analysis were assumed from recommendations within the previously commissioned energy network project reports.

A clearer statement of each relevant assumption is provided preceding the appropriate section in the following chapter on Methodology.

4 Methodology

This chapter of the report aims to explain and set out each of the processes and analytical procedures carried out in the project; this includes outlining the comparative methods applied in the assessment of the load demand matching processes, a breakdown of the calculations and processes used in the investigation of potential waste heat applications and also the method applied to assess the impact of future changes to the campus infrastructure. Any assumptions made in the following analyses are stated at the beginning of the appropriate section.

4.1 Load Demand Matching

This section is subdivided into three segments with the purpose of defining the analytical procedures applied to the monthly, daily and half-hourly data in the pursuit of the stated project goals; the procedure used in the creation of the demand profiles used for the Sports Centre and the Technology & Innovation Centre is set out in a fourth and final segment.

4.1.1 Assumptions made

The following represent the assumptions made for the purposes of the ensuing analysis, the justification of which can be found in Appendix 4.

Profile Matching Assumptions

- The system is assumed to operate at a heat to power ratio of 1:1.
- Recorded Gas demand is assumed to be equal to heat demand.
- Where missing data has been encountered, that data from an equivalent time step has been assumed to be an appropriate replacement, as defined in the Data Analysis section (3.3) above.

4.1.2 Analytical Process

The purpose of the data processing and breakdown demonstrated in the sections below is to generate load profiles for the heat and power demands of the campus that will allow conclusions to be achieved with regard to the performance of the network variations being investigated.

Initially, the load demand comparison is used to generate a visual representation of the heat to power demand over the period of analysis, building a clearer picture of the energy interactions of the numerous system variations. The true analysis of the system performance however is applied through investigation of the Heat to Power Ratios (HPR)s for each variation; the three phases with the best-matched heat demand for each electrical variation are to be summarised in a table where assessment of the maximum, minimum and average values can be accomplished. Where it is not possible to identify the best-matched phases through graphical analysis the maximum, minimum and average for each network combination will be calculated to find the three most appropriate. In the perfect system each of these would be 1; therefore, the network variation that produces the value closest to this ideal will be identified as the best-matched system.

More flexibility is granted for the maximum and minimum values as these can possibly be met through peak load shifting, heat storage or other techniques. If the average HPR value surpasses 1 however the system will be disregarded, as more demand is required for that arrangement than is available through the network.

By seeking the data set with a maximum and minimum HPR best suited to the networks demands, and with and average demand closest to 1, the most appropriate combination with lowest waste heat and highest percentage heat demand met for that time frame is found.

With regard to the half-hourly data set, alongside analysis of the half-hourly HPR, the HPR results were averaged into a more manageable daily format; this facilitated a direct comparison with the results of the HPR calculated over both the daily and monthly timeframes as defined above to assess the quality of each results set.

It is also worth noting that each time an equation was entered into Excel as part of the numerical analysis process the integrity of the data sheet was assessed via the Trace Precedents and Error Checking tools within the program. These are by no means a guarantee of robust data analysis, although their application combined with manual error checking for data spikes and other various indicators of erroneous data should keep the error count as low as practicably possible.

4.1.3 Monthly Data Analysis

The first and most direct of the load demand matching analyses makes use of the manually recorded monthly data for this primary assessment of the energy networks viability. As explained in the Data Processing section (3) above, the manually recorded monthly data for both electrical and gas consumption was provided as separate spreadsheets, each building listed individually in each sheet with the monthly consumption listed in a column next to the building name.

At this stage it is worth noting that the original presentation of the data set in an ascending column simplifies the analysis process, as many of the analytical functions within the Excel program rely on data being formed in either columns or rows.

The first step in processing this data into a form that can be used for analysis is to collect the individual monthly demand data for each building and create a table, one for both the gas and electrical consumption. These tables are then sorted to collect each of the phases in a row of columns, with the monthly sum total for each phase at the end of each row.

The totals are then arranged for analysis. The gas demand is taken directly from the phase totals for each month, while the electrical demand totals must be summed according to the substation from which the building is supplied as taken from the electrical schematic of the campus. These two data sets are then collected into one sheet and lined up for comparison.

The next stage in the analysis of the monthly data is the calculation of the HPR for each of the phases, using the monthly totals. This is simply the ratio between the heat and electrical demand, with the gas representing the high-level heat demand in this case, and is calculated as shown in Equation 4:1 below.

- Heat to Power Ratio Calculation:

$$HPR = \frac{Heat\ Demand}{Electrical\ Demand}$$

Equation 4:1

The HPR is then calculated for each defined phase of the heat network development against the four progressive electrical demand phases, to represent and analyse each set of demand combinations.

The method of applying this heat to power analysis to the collected data within excel started with inserting a column between each heat demand phase for every stage of electrical network expansion. An example of this process can be seen below in Figure 4:1.

ELECTRICITY		GAS
Central Sub	Phase 1	P1 - E1
2658587	470050	0.1768
2098819	605644	0.2886
2354147	1289268	=G7/C7
2456877	2238012	0.9109

Figure 4:1 - Example of Heat to Power Process in Excel

Once the HPR has been calculated for each combination the comparative analysis can be performed to obtain the ideal network arrangement according to the monthly demand data. This is accomplished via two methods: by comparing the load demands directly and analysing the HPR phase by phase.

4.1.4 Daily Data Analysis

This second, daily form of consumption data analysis is a more complex procedure than encountered in the monthly analysis section. One of the first factors adding to this complexity is the difference in the presentation of the data. Daily data for both electrical and gas demand is taken from each respective half-hourly data set, however both present the data in a different manner and so must be processed differently.

Daily gas demand is clearly set out in the half-hourly gas data set, automatically summed as a total of the half-hourly data for that day.

This is not the case with the electrical consumption data set, in which the daily total must be calculated manually. This is done by summing each twenty-four hour period in the data set in the cell adjacent to the final half-hourly reading of each day. This column is then filtered by removing the blank cells to present a list of data solely made up from the summed daily totals that can then be used for analysis.

At this stage in the analysis of the daily data it is once again important to note that the summed daily total is presented as one ascending column in both half-hourly data sets, once again making the analysis of this data a fairly straightforward process. The data processing methodology applied to the daily data for use in the analysis can be found in Appendix 5.

The final daily data set allows for the high-level gas heating loads of each Phase to be accurately compared with the electrical loads from the four progressive electrical demand Stages, followed by the generation of the relevant HPR.

This represents the final step in the daily data processing methodology and from here an analysis of the load demand can be carried out, seeking the most appropriate heat and power infrastructure combination for the site according to the daily demand data using the HPR and load demand comparisons detailed above.

4.1.5 Half-Hourly Data Analysis

Analysing the half-hourly data in assessing the demand loads for the proposed energy network is by far the most detailed of the three analytical methods used, and as such it is also the most challenging and complex.

The electrical data set requires the least processing for this analysis due to the alignment of the half-hourly electrical data in one single column. The only processing required from the electrical data at this stage is to split the data between the Central and Graham Hills substations as was performed above in the daily data analysis.

Due to the horizontal alignment of the half-hourly gas data, which arrays the data set in a matrix format, more complex processing is required to align the spreadsheet as necessary for desired analysis. The methodology and data processing techniques applied to the half-hourly data set can be found in Appendix 6, with the macro written to convert the data from matrix to column format shown in Appendix 7.

With the complete half-hourly data set arranged into the desired format, the heat to power demand analysis can be undertaken using both direct load comparison and HPR data.

4.1.6 Data Profiling & Analysis

As both the Sports Centre and TIC Building had not been built at the time of writing the data required to include them in the analysis of the energy network must instead be generated. The methods for generating and profiling this data are not simply created but rather built from what information is available for these buildings pre-construction.

As the actual energy demand for either site is currently unknown, in a necessary exception to the desired aims of this project, the data sets for these sites are to be generated from simulated data sourced in the pre-construction Energy Performance Certificates (EPCs) and demand load models that must be commissioned and issued before work can start on a development. The anticipated demand data for the Sports Centre was sourced from the Strathclyde Stage 2 Proposal document (Estates Dept. University of Strathclyde, 2012), with the data for the TIC Building sourced from the BRUKL document (University of Strathclyde , 2012) prepared before its construction commenced. The anticipated demand for each site can be seen in Table 4:1 below.

Table 4:1 - EPC Demand Data for Sports Centre & TIC Building

Sports Centre & TIC Energy (EPC data)									
Building		Electrical					Gas		
Name	Area (m2)	Cooling	Aux	Lighting	Eqpt	Total (kWh/y)	Heating	HW	Total (kWh/y)
TIC	17374.8	0.33	12.05	7.96	59.78	1392069	18.6	11.46	522286
SP	8500	-	-	-	-	901000	-	-	2795000
		(kWh/m2)					(kWh/m2)		

These figures for total annual heat and power demand for the sites can now be applied to monthly, daily and half-hourly annual demand percentage profiles to facilitate their analysis alongside the recorded demand data.

Before the annual demand profile can be created it is important to carefully select the appropriate data set to be used as a base; it is from this that the percentage profile in the final data set will be generated. The Central substation was chosen to represent the electrical demand profile and two different profiles were selected to represent the heating profile of the sites; the Sir William Duncan building for the TIC building, with the Curran building to represent the Sports Centre.

The profile is then generated by building up each required division as a finite percentage of the annual total demand in that data set. For example, if the spread of data across the year was equal this would equate to 1/12th of the total for each monthly representation, 1/365th divisions for daily representations and 1/17520th divisions of the annual demand to represent half-hourly data.

The profiles should be based upon the half-hourly data sets of the selected sites, as this will allow the generation of percentage profiles down to this timeframe, which will be required for the desired analysis. The profiling of the gas data therefore requires additional processing, using the macro defined in the section above, once again arraying the half-hourly data into a column rather than matrix form. With each of the three data sets now arrayed as an ascending column the percentage profiles can be created.

The first step in the creation of the percentage profile is to calculate the sum of the demand over the entire year, achieved by summing the column of half-hourly demand in its entirety. The half-hourly percentage profile is generated by dividing each half-hourly data entry by this annual total to calculate the fractional worth of the value for that time, fixing the reference for the annual data as seen below in Figure 4:2.

Sports Centre (Curran)			
Date	Time	kWh	HH (Y %)
30/06/2013	18:00	189.803	0.00010683
30/06/2013	18:30	126.535	7.1223E-05
30/06/2013	19:00	158.169	8.9029E-05
30/06/2013	19:30	126.535	7.1223E-05
30/06/2013	20:00	126.535	=P9308/$P$9317
30/06/2013	20:30	126.535	7.1223E-05
30/06/2013	21:00	126.535	7.1223E-05
30/06/2013	21:30	158.169	8.9029E-05
30/06/2013	22:00	63.268	3.5612E-05
30/06/2013	22:30	0	0
30/06/2013	23:00	0	0
30/06/2013	23:30	0	0
30/06/2013	00:00	0	0
	Total	1776599.74	

Figure 4:2 - Example of Half-hourly Percentage Calculation

The creation of the daily percentage profile originates with the calculation of a demand total for each day. As the divisions in the data set are equal, applying this calculation to every daily cluster in the data set can be undertaken by summing the half-hourly demand for one day then copying the cell containing the formula along with all proceeding cells for that day and pasting the selection down the entire data set.

These daily totals can then be divided against the annual total, just as in the half-hourly profile generation, to calculate the fraction of that annual total represented by each day. This calculated daily fraction is achieved for each set of daily data with the same technique that was applied to calculate the daily total.

The monthly totals are achieved in much the same manner as the daily demand totals, although in this case summing the daily totals rather than the half-hourly demand. However, as each month varies in length, when the formula is copied down it must be adjusted to sum the correct the number of days.

With annual percentage profiles created for all the necessary data sets it is now possible to combine these with the anticipated annual energy demand, multiplying the latter by the former to generate the required demand profiles for both the Sports Centre and TIC building. An example of the demand profiles generated for the Sports Centre can be seen below in Figure 4:3.

Sports Centre									
Monthly (kWh)			Daily (kWh)			Half-Hourly (kWh)			
Month	Gas	Electrical	Date	Gas	Electrical	Date	Time	Gas	Electrical
Dec	121666.597	74428.5545	19/12/2012	11937.5456	2755.89801	19/12/2012	00:30	0	45.8071329
Jan	320474.971	81367.1149	20/12/2012	11540.4341	2661.25089	19/12/2012	01:00	0	45.7124248
Feb	277966.617	78119.0462	21/12/2012	10064.0733	2315.87068	19/12/2012	01:30	0	45.9176256
Mar	301364.557	84510.4809	22/12/2012	4228.76554	1645.42251	19/12/2012	02:00	0	45.5703627
Apr	415452.647	78310.0474	23/12/2012	1216.20673	1631.62279	19/12/2012	02:30	0	45.5387933
May	264776.89	77297.3175	24/12/2012	14086.7599	1805.75456	19/12/2012	03:00	0	45.3335925
Jun	200245.439	67430.3052	25/12/2012	12477.0011	1761.27127	19/12/2012	03:30	0	44.48122
TOTAL	1901947.72	541462.867	26/12/2012	13057.4463	1762.37582	19/12/2012	04:00	0	44.5443587
			27/12/2012	12969.966	1841.94653	19/12/2012	04:30	0	45.3335925
			28/12/2012	10730.6512	1797.8649	19/12/2012	05:00	0	45.8071329

Figure 4:3 - Example of Profiles Generated for Sports Centre

These energy demand profiles can now be entered into the appropriate monthly, daily or half-hourly data set along with each of the other potential energy network phases for analysis; ensuring the load demand matching analysis in this project is performed using as accurate a representation of the actual campus demand as it was currently possible to achieve.

The expanded electrical demand profiles assumed for the energy network, now inclusive of this profiled data, are defined as shown below in Table 4:2.

Table 4:2 - Staged Electrical Demand Expansion

Staged Electrical Demand Expansion	
Stage 1	Central Substation
Stage 2	Central Substation + Sports Centre
Stage 3	Central Substation, Sports Centre + Graham Hills Sub
Stage 4	Central Substation, Sports Centre, Graham Hills Sub + TIC Building

4.2 Heat Demand Shifting

This section is subdivided into two segments with the purpose of setting out both the analytical procedures applied to the half-hourly demand data and the calculation methods employed in the pursuit of the stated project goals.

4.2.1 Assumptions made

The following represent the assumptions made for the purposes of the ensuing analysis, the justification of which can be found in Appendix 4.

Profile Matching Assumptions

- The system is assumed to operate at a heat to power ratio of 1:1.

- Recorded Gas demand is assumed to be equal to heat demand.

- Where missing data has been encountered, that data from an equivalent time step has been assumed to be an appropriate replacement, as defined in the Data Analysis section (3.3) above.

Heat Storage Calculation Assumptions

- The storage vessel is assumed to be cylindrical with a height of 4m, diameter of 2m and a volume capacity of 100000 litres, as suggested in previously commissioned reports (Palmer & Tamburrini, 2007).

- The contact area of fluid in the storage vessel is assumed to be equal to the total internal vessel surface area, which is also assumed to be equal to the external surface area.

- The temperature of the area in which thermal storage vessel is stored (T_e) is assumed to be constant at 18^{o}C or 291K.

- The storage vessel is assumed to be a fully mixed capacity of liquid storage with a uniform temperature, initially assumed to be 110^{o}C or 383K (T_k) as suggested in previously commissioned reports (Palmer & Tamburrini, 2007).

- The energy stored in the vessel is assumed to initially be in a balanced state.

- The storage vessel is assumed to be at full capacity.

- The fluid contained in the storage vessel is assumed to be water.

- The material of the storage vessel is assumed to be Galvanised Steel with a wall thickness of the 5mm.

- The insulation material for the vessel is assumed to be mineral wool with a thickness of 200mm, as suggested in previously commissioned reports (ARUP, 2012).

- It is assumed that the storage vessel is perfectly insulated, with losses through any connections to the vessel ignored.

- Transmission losses from the CHP generator to the storage vessel or from the vessel to the demand location are also ignored.

- The specific heat capacity (C_p) of water is assumed to be constant at 4.187kJ/kgK.

- The conversion ratio between kilograms (kg) and litres (l) of water is assumed to be 1:1 (ME928 - Energy Systems Analysis, 2012).

Cooling Analysis Assumptions

- In the absence of chiller demand or consumption data it is assumed that EPC data, applied to a simulated cooling demand profile, will be accurate within the scope for this analysis.

- It is assumed that all the profiled cooling demand for the campus is met by electrical sources, and as such is represented in the electrical load.

- The Absorption Chiller system is assumed to be a lithium bromide cycle with a coefficient of performance (COP_{ABS}) of 0.7 (CIBSE, 2012).

- Both the transmission losses from the CHP generator to the chiller system and from said system to the point of demand are ignored.

- It is assumed that any electrical demand resultant from the use of the absorption chiller from pumps & fans etc. are outwith the scope of this analysis and therefore are equal to zero.

Esp-r Simulation Assumptions

- The degree of the Sports Centre's electrical load that is represented by cooling is assumed to be 10%.

- It is assumed that the cut in temperature of the cooling system modelled with Esp-r is 18^{o}C.

- Computer Lab 2, located on the 3rd floor of the University of Strathclyde's Curran Building, is estimated to be 10m x 10m in size.

- Computer Lab 2 is assumed to have lighting equivalent to CIBSE classroom standards for compact fluorescent lighting at 500 lux and 14W/m^2 with 30% heat output (CIBSE, 2012).

- Computer Lab 2 is assumed to have full occupancy throughout each weekday and half occupancy in the evenings and at weekends, with occupancy profiles based upon Curran Building term-time opening hours for the 2012-13 academic year.

- Occupancy gains are assumed to be equivalent to CIBSE standards for moderate office work at 75W sensible and 55W latent heat gains per person (CIBSE, 2012).

- The electronics in Computer Lab 2 are assumed to be equivalent to CIBSE standards with gains for each computer totalling 135W through the day and 25W at night (PC and Screen inclusive) and a constant 125W to represent the laser printer at idle.

4.2.2 Analytical Process

The purpose of the data processing and breakdown demonstrated in the sections below is to assess the viability and potential impact of heat demand shifting on the proposed campus energy network through both the application of a thermal storage system or the use of waste heat for cooling.

The thermal assessment is based upon the variable availability of waste heat from the network for each phase of the development, using daily time steps for practicality. This availability is assessed based upon a graphical representation of the profile along with the maximum, minimum and average values. The graphical representation provides a visual guide to the system performance while the maximum and minimum values indicate the greatest quantity of heat available or removed from the storage vessel respectfully. It is important to analyse the results both graphically and in tabular form as only through this combined analysis can a true picture of the system operation be formed for each combination.

There are two key results which are critical in defining whether a system can be deemed viable or not; these are the mean and the minimum value for each results set. If the average value is shown to be negative then the system is not sustainable as more heat is required from the storage vessel than is available to be stored. If the minimum value is shown to be positive then the system is sustainable but the heat storage system is shown to be surplus to requirements, as heat is only added to the storage vessel with no additional heat required; these combinations are still viable options although, due to the high levels of heat wastage that will result from this arrangement, they are unlikely to be judged a best-matched option. Exceptionally low minimum values are also detrimental to the potential for the system as they indicate a heavy reliance on stored thermal energy to meet the demand on occasion.

Therefore, any network combinations with a negative average value can be removed from the analysis, as the thermal storage system is not sustainable for these arrangements. Any network combinations shown to have a minimum value with greater magnitude than the maximum value will also be disregarded from the analysis as their demonstrated reliance on stored heat highlights a potentially unstable energy system.

Through this visual and numerical analysis the network combination that sustainably make use of the most potential waste heat, and as such the best matched system variation, can be identified as the system with the best matched minimum and maximum profiles throughout the analysis combined with the most agreeable demand profile. These are defined more accurately requiring the maximum available heat around 20% greater than the maximum demand, with the profile clearly shown to be typically above the datum for the greater portion of the analysis and an average demand not greater than half of the maximum heat available.

The potential for using waste heat to meet cooling demand on the campus is assessed by combining the required heat to meet this demand through absorption chilling with the heat demand for each phase. The electrical energy that would have previously met this demand is simultaneously subtracted from the electrical profile for that phase. The impact of this alternate energy use is quantified though re-running the daily load demand matching exercise, as set out in the section above, using this adjusted demand profile.

As with the demand matching analysis, each time an equation was entered into Excel as part of the numerical analysis process the integrity of the data sheet was assessed via the Trace Precedents and Error Checking tools within the program. Again, these are by no means a guarantee of robust data analysis, although their application combined with manual error checking for data spikes and other various indicators of erroneous data should keep the error count as low as practicably possible.

4.2.3 Assessment of Waste Heat Potential

The first step in the assessment of potential waste heat from the system should be gathering all of the necessary, half-hourly data sets into one spreadsheet for ease of analysis and manipulation. This includes the demand profiles created for the Sports

Centre and Technology Innovation Centre, as defined in the preceding section on data profiling and analysis.

Once the data has been collected it should be arranged in a form clearly illustrating the increased demand brought about through the incremental inclusion of each phase, for both heat and power demand. The heat generation data sets, as represented by the electrical demand at a 1:1 Heat to Power ratio (HPR), are combined in order from the Central Substation to include the demand from the Sports Centre, the Graham Hills Substation and finally the Technology Innovation Centre.

A similar process is then carried out for the heat demand, as represented by the recorded gas demand for each phase, progressing to include Phases 1 through 10 in single-phase increments.

With both the potential supply and demand summed accordingly, the next stage in the process is to adjust the demand data to represent hourly demand rather than its current half-hourly form. This is performed to simplify the coming analysis through allowing the more practical conversion of hourly-metered data from kWh to kW, as required later in the process.

The demand data is arranged into an hourly format by first summing the demand over each hourly period. As defined in the Data Processing section above, the half-hourly data is representative of the energy demand of the system for that half-hourly period; 00:30 representing the demand from 00:00 up to this time and so on. The total demand for each hour is therefore the sum of the data listed at that hour plus the preceding half hourly data recording, as shown below in Figure 4:4.

		Combined E (Heat Generated)				
Date	Time	Central	C + SC	C, SC+GH	C, SC, GH + TIC	Central
19/12/2012	00:30	1451.000	1496.807	1697.507	1768.280	
19/12/2012	01:00	1448.000	1493.712	1693.412	1764.039	2899.000
19/12/2012	01:30	1454.500	1500.418	1700.418	1771.362	
19/12/2012	02:00	1443.500	1489.070	1688.970	1759.378	=SUM(D7:D8)

Figure 4:4 - Hourly Demand Process

The demand is summed on every second row with the rows numbered to allow data filtration and the subsequent summary of the now hourly demand.

The hourly demand data is then split between the four incremental heat generation data sets defined above with a new sheet for each variant to allow comparison of how the available heat at each stage compares with the phased demand.

The variation between demand and generation is then calculated for each phase by subtracting the required demand from the possible supply, thereby demonstrating whether the energy balance is in excess or deficiency at each time step.

The next step is to determine the variation between the supply and demand for each day, calculated by summing the hourly variance to illustrate whether the energy network has the capacity to provide the heat demand for that phase for each day in the analysis.

These daily data sets quantify the waste heat available for each iteration of the heat and power network; therefore allowing the potential of each combination to be thoroughly assessed for possible further analysis. The results of this initial assessment will allow the value and potential benefit of any further analysis achieved into waste heat use to be quantified.

4.2.4 Demand Matching through Heat Storage

With both the availability and absence of potential waste heat now calculated for all iterations of the proposed heat and power network, it becomes possible to assess the potential for energy storage in the network to facilitate effective heat load shifting through the use of stored energy to match the demand of the system. This analysis was performed through the application of the following methodology.

The process of assessing this potential for heat demand matching begins with the division of the suggested heat supply phases undertaken in the initial Assessment of

Waste Heat Potential section above. Each energy supply variation is therefore copied into an individual sheet for detailed analysis.

The method developed to assess this potential involves the quantification of waste heat generated by the system for each hourly time step, which can then be stored in a clearly defined system for the purpose of matching the demand of later time steps.
The progression of this analysis is illustrated by the following example, considering concurrent hourly time steps 1, 2 and 3:

The heat demand is subtracted from the heat generated by the system at Step 1, resulting in a figure for waste heat at this time step. This waste heat from time Step 1 is then carried to the next time step in the analysis, Step 2, and combined with the heat generated for that time step to represent the total heat available at Step 2. The heat demand for time Step 2 is then subtracted from this total to represent the demand matching at that stage and the resulting figure, the total waste heat available after Step 2, is now carried on to be added to the heat generated in the time step 3. Heat energy losses from the vessel are also calculated for each Step and subtracted from the total energy available at that time step in addition to the demand.

As stated in the assumptions section above, the storage vessel is assumed to be a fully mixed capacity of liquid storage with a uniform temperature and the energy of the vessel is assumed to be initially balanced. No additional waste heat is therefore added to the primary row in the analysis, allowing this investigation to simply represent the additional waste heat available to be stored in this already balanced vessel without the application of any energy possibly stored prior to the first time step. The calculation method applied in the analysis of each data set is defined below.

4.2.4.1 Waste Heat Analysis – Calculations & Formula

The equation below is used as the basis for the analysis of potential storage and use of waste heat in the system.

- Energy balance equation:

$$Q_u - Q_l - Q_{tl} = (m.C_p)_s \frac{dT_s}{dt}$$

Equation 4:2[3]

Where,

Q_u = Rate of energy delivered to storage vessel (kW)

Q_l = Rate of energy leaving storage vessel (kW)

Q_{tl} = Rate of energy loss from storage vessel (kW)

m = Mass of water in storage vessel (kg)

C_p = Specific heat capacity of water = 4.187 kJ/kgK

$\frac{dT_s}{dt}$ = Change of temperature in the vessel over time (K/s)

The desired analysis of the thermal storage potential requires the introduction of another variable into this equation, the rate of energy stored Q_s. This term is applied to the left hand side of the equation (Eq. 4.3) to quantify the energy that is either available for, or required from, the storage vessel for each time step. The equation considers the energy balance of the time step in question when combined with the energy stored in the storage vessel, to represent the total energy available at that time step, and is defined as shown below.

- Energy storage calculation:

$$Q_{s2} = Q_{u2} - Q_{l2} - Q_{tl2} + Q_{s1}$$

Equation 4:3

Where,

Q_{s2} = Rate of energy stored at time step 2 (kW)

Q_{u2} = Rate of energy delivered to storage vessel at time step 2 (kW)

Q_{l2} = Rate of energy leaving storage vessel at time step 2 (kW)

Q_{tl2} = Rate of energy loss from storage vessel at time step 2 (kW)

Q_{s1} = Rate of energy stored at time step 1 (kW)

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[3] (Cabeza, 2012)

The terms Q_{u2} and Q_{l2} are represented as the heat generated and demanded at each time step respectively. Q_{s1} represents the energy available from storage after the previous time step, while Q_{s2} represents the resultant energy stored after the energy balance is carried out for the time step in question. Q_{tl} represents the losses of the time step under analysis and is calculated as defined below.

- Equation for calculation of losses:

$$Q_{tl} = (U.A)_s(T_s - T_e)$$

Equation 4:4[4]

Where,
U = U-Value of storage vessel (W/m^2K)
A = Contact area of fluid in vessel (m^2)
Ts = Temperature of fluid in storage (^oK)
Te = Temperature of area in which vessel is stored (^oK)

Of these values only the temperature of the area in which the vessel is stored is known; as stated in the assumptions section above, this is taken to be constant at 18^oC (291K). The U-value and Area of contact of the fluid in the vessel must be calculated. However, while the initial temperature of the fluid in storage is assumed to be 60^oC (333K), the internal temperature (T_s) is a value that will fluctuate with the addition and extraction of energy from the vessel and therefore must be calculated for each time step. The methods applied in the calculation and derivation of these functions is defined below.

As stated in the assumptions section above, the Area of contact of the fluid in the storage vessel is assumed to be equal to the total internal surface area of the vessel in question. Both the surface area and the U-value can be calculated through a standardised process, as defined in Appendix 8. The results of this calculation can be seen below.

$\underline{A = 135.66\, m^2}$ $\underline{U = 0.19\, W/m^2K}$

[4] (Cabeza, 2012)

With the storage vessel area and U-value now calculated, the last function required in to calculate the rate of energy loss in the system (Q_{tl}), is the variation in temperature of the storage vessel for each time step; the derivation of which was performed as follows.

- Temperature change derivation:

Beginning with the energy balance formula (Eq. 4:3),

$$Q_u - Q_l - Q_{tl} = (m.C_p)_s \frac{dT_s}{dt}$$

$$\frac{dT_s}{dt} = \frac{(Q_u - Q_l - Q_{tl})}{(m.C_p)_s}$$

Equation 4:5

The specific heat capacity of water (C_p) is, as stated in the assumptions above, assumed to be a constant value at 4.187 kJ/kgK.

Finally, considering the assumed volume of the water in the storage vessel is 100000 litres, the mass of the water can be assumed to be 100000 kg as the mass conversion ratio between the two units is [1:1][5].

Mass of water in storage:

$$\underline{m = 100000\ kg}$$

This formula (Eq. 4.10) can now be entered into the spreadsheet to calculate the incremental changes in the temperature of the storage tank at each time step, which is required to accurately calculate the losses (Q_{tl}) used in determining the overall energy balance. The application process for this analysis can be found in Appendix 9.

[5] (ME928 - Energy Systems Analysis, 2012)

With all of the necessary formulas achieved and the required constants calculated the next stage in the process is the application of this calculation method to the collected, hourly data set as defined above at the start of this section on demand matching through heat storage.

4.2.5 Use of Waste Heat for Cooling

As stated in the data processing and assumptions section above, no recorded cooling demand data was available for this analysis. It was decided therefore to base the analysis on simulated data; specifically, a combination of recorded annual electrical data, percentage cooling demand taken from EPC data and a cooling profile created through simulation with Esp-r software. This simulated data will be used to calculate the cooling load required for each development phase in the proposed energy network; this profiled cooling demand will then be used to calculate the heat demand required to meet this cooling load through Absorption chilling systems. The application of these techniques was carried out using the following methodology.

4.2.5.1 Use of Waste Heat for Cooling - Percentage Demand Profiling

The first step in achieving the desired demand profiles for the cooling analysis was to investigate the EPC certificates available for each building. As stated in the data processing section (3) above, in the absence of recorded demand data these certificates can provide a rough outline of the anticipated energy consumption for a building; as such, where a building has cooling installed it will be represented in the EPC as a percentage of annual energy use. This initial investigation of the EPC data for each building is then broken down and summarised, as shown in Figure 4:5 below.

EPC Data Calcs/Percentages

Building	Total	Vent	Main H.F	Building	Total	% H	% HW	% Elec (L)	% Elec (E)	% Aux	% Cool	Total H	Total Elec
Architecture	372	Nat	Gas	5325.29	1981008	70	1	13	14	2	0	1406515.59	574492.29
Barony Hall	738	Nat	Gas	2021.43	1491815	82	0	5	2	10	0	1223288.58	253608.61
Collins Building	327	Mech	Gas	1421.38	464791.3	51	2	22	5	20	0	246339.37	218451.89
Colville Building	250	Nat	Gas	12449.1	3112275	63	1.5	14	13	8	0.5	2007417.38	1089296.25
Curran Building	282	AC	Gas	26619.5	7506699	28	0	11	26	22	13	2101875.72	4428952.41
Graduate School	164	AC	Gas	5825.83	955436.1	37	3	22	20	12	6	382174.45	515935.50
Graham Hills Bui	265	Nat	Gas	19972.5	5292713	68	1	16	11	3	1	3651971.63	1587813.75
Henry Dyer Build	290	Nat	Gas	2620.42	759921.8	65	0	15	10	7	3	493949.17	243174.98
James Wier Build	250	Mech	Gas	21067.4	5266850	60	3	15	13	8	2	3318115.50	1896066.00
John Anderson B	253	AC	Gas	10656.6	2696120	49	3	18	14	16	3	1401982.30	1294137.50
John Arbuthnott	229	Nat	Gas	3385.91	775373.4	54	2	21	15	5	3	434209.10	317903.09
John Arbuthnott	166	AC	Gas	8944.87	1484848	29	2	25	28	11	4	460303.01	950302.99

Figure 4:5 – Excerpt from EPC Summary Table

The percentage consumption data is then recalculated as a percentage of electrical rather than total annual demand, with the total electrical demand calculated from the cooling, auxiliary and lighting requirement. This recalculated percentage can then be applied to the recorded annual electrical demand for the site to generate a applicable cooling demand total for that building. The process applied in the recalculation is demonstrated in the example below.

- Cooling as a Percentage of Electrical Demand:

Total Annual Energy Demand = 250000 kWh

Total % Cooling Demand = 10%

⇨ Total Cooling Demand = 250000×0.1

⇨ Total Cooling Demand = <u>25000 kWh</u>

Total Electrical Demand = 150000 kWh

Total Cooling Demand = 25000 kWh

⇨ Electrical % Cooling Demand = $\left(\frac{25000}{150000}\right) \times 100$

⇨ Electrical % Cooling Demand = 17%

This process is performed for each site included in the analysis where mechanical cooling is present and then applied to the total electrical demand to create an annual cooling load.

The manually recorded monthly demand data set was used to calculate the total electrical demand for each site, as building specific half-hourly electrical data was not available for this analysis. In the case of both the Sports Centre and the TIC Building, the monthly demand data generated through the percentage profile process, as defined in the section (4.1.5) above, was used.

To accommodate the later analysis each of the buildings without any cooling load should be removed from the table; this will greatly simplify the analytical process as it removes several buildings and phases from the analysis altogether. The annual cooling demand totals are now arrayed in a form that can be applied to the cooling demand profile achieved through Esp-r simulation. The details of this simulation process are defined below.

- Esp-r modelling process

Before an explanation of the simulation process can begin, it must be stated that Esp-r simulation software is an incredibly powerful but also very complex program to use. Once the modelling process was begun it became clear very quickly that some limitations would have to be applied to the use of the program to keep this section of the analysis within the original scope of the thesis project. At this time it was decided, as defined in the data processing section (3) above, that due to the complex nature of the program and the simulation required it would be more appropriate to generate a percentage demand profile from annual data for temperature and internal gains rather than extract a cooling demand profile from the simulation as was originally planned.

The purpose of the simulation is therefore to assess the cooling demand of a set zone, which is modelled with loads and gains representative of a typical computer lab on the University of Strathclyde campus.

The model selected was an exemplar found in the software, listed in the realistic scale directory and defined as “Office with Natural Ventilation”. The model itself is shown in Figure 4:6 below.

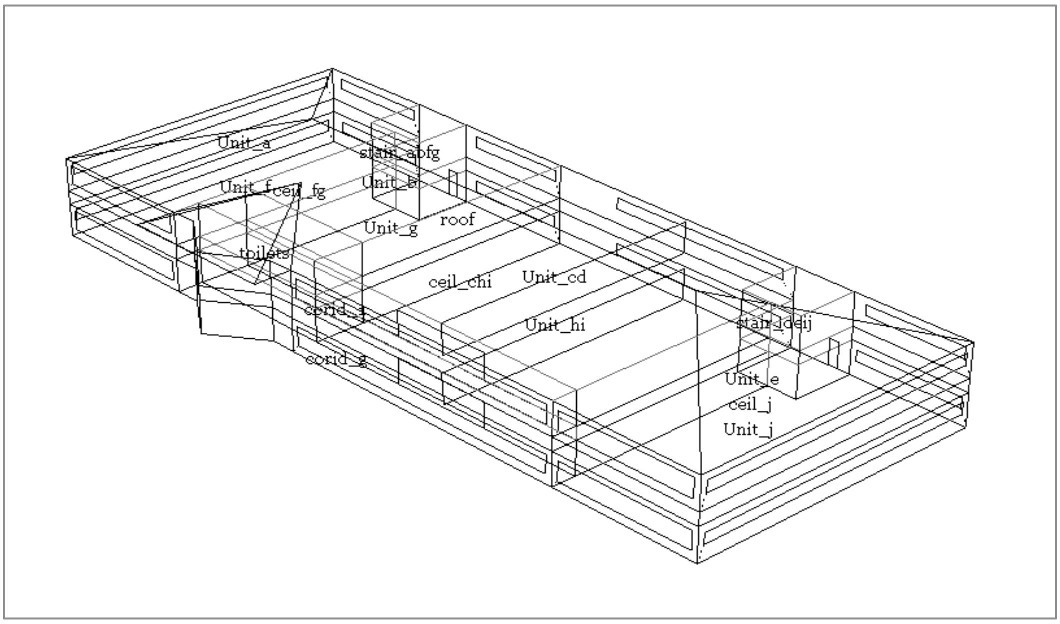

Figure 4:6 - Esp-r Model: Office with Natural Ventilation

The internal office space "Unit_hi" was selected to be the focus of this simulation, as seen in Figure 4:6 above. To ensure the accuracy of the input, and therefore also the results of the simulation, the computer lab "Lab 2" on level 3 of the Curran Building was visited and surveyed.

The lab was estimated to be 100m^2, contained 27 PC terminals with one laser printer and was serviced by what was assumed to be compact fluorescent lighting. The values assigned in the model to represent these internal gains, assumed to be CIBSE standard for the room type, and the associated weekly profiles are listed in Tables 4:4 and 4:5 below.

Table 4:3 – Internal Gains (CIBSE, 2012)

	Full Occupation/Active			Unoccupied/Idle		
Gain	Number	Sensible (W)	Latent (W)	Number	Sensible (W)	Latent (W)
PC + Screen	27	135	0	27	25	0
Laser printer	1	125	0	1	125	0
People	27	75	55	0	0	0
Lighting	N/A	4.2 (W/m^2)	0	N/A	0	0

For these gains to be accurately represented in the simulation, they first had to be converted into a form that facilitated a like-for-like representation of these internal gains in the model. By calculating the total figure for each fixed internal gain present in "Lab 2", it then becomes possible to calculate the gain per square meter (as already present for the lighting gain) of the zone; these area dependent gains can then be entered into the model as an accurate representation of the set gains from "Lab 2". The conversion of the internal gains from fixed to area dependent values is shown below in Table 4:5.

Table 4:4 - Calculation of Area Dependent Gains

Area (m^2) =	100	Area Dependent Gains		
Gain	W	Frequency	Total Gain	T-Gain/m^2
Occupant (S)	75	27	2025	20.25
Occupant (L)	55	27	1485	14.85
PC (Active)	135	27	3645	36.45
PC (Idle)	25	27	675	6.75
Laser Printer	125	1	125	1.25

The gains, as calculated in Table 4:5 above, are now capable of accurately representing the computer lab. The next step in the modelling process is therefore to apply these gains to demand profile representative of an anticipated pattern of use. As stated in the assumptions above, the demand profile created for this simulation was based upon the term time opening hours for the Curran Building as described below:

- Profiling of Internal Gains

Full occupancy was assumed on weekdays from 08:00 to 18:00 hours with half occupancy for all other occupied periods. The internal gains for half occupancy were represented in the profile by applying only 50% of the calculated gains for both Occupants and PCs, while including 50% of the gains representing idle PCs. The laser printer and lighting gains were represented at 100% for all occupied time periods. The only internal gains present for unoccupied periods were 100% of the gains representing idle PCs and the laser printer.

The gains profiles as defined in Esp-r are shown in Figure 4:7 below, a full breakdown of the simulated internal gains can be seen in Appendix 10.

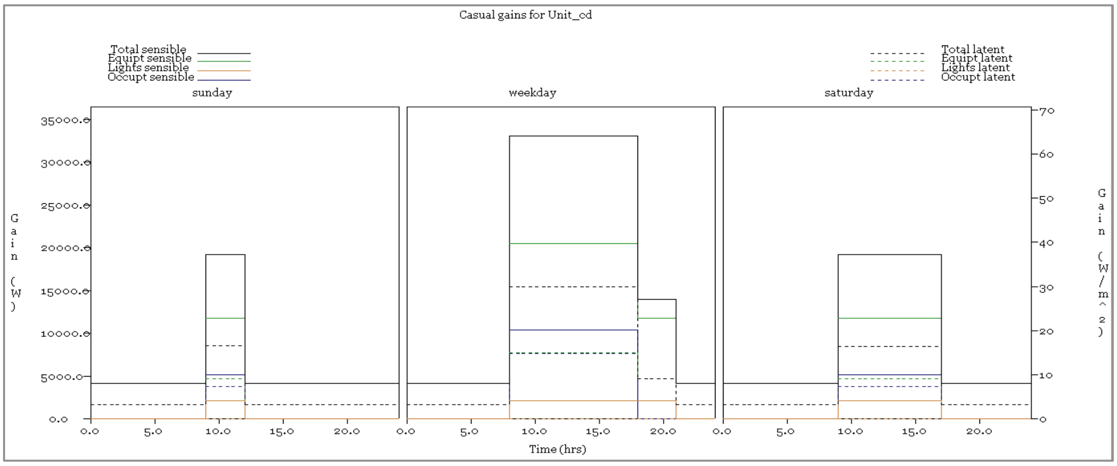

Figure 4:7 - Illustration of Esp-r Internal Gains Profile

With the gains calculated and profiled into the Esp-r program it is now possible to prepare and run the simulation. The details entered into the Esp-r interface to achieve the desired results were as follows:

Simulation start-up days =	8
Time steps per hour =	2
Simulation length =	01 Jan – 31 Dec
Weather file =	clm67

An integrated simulation was then run for the model, from which the results for the annual Internal Temperature of the zone “Unit_hi” were then exported from the Results Analysis function within Esp-r.

The results requested from the program were found in the Time-step Reports section of the Results Analysis interface. The data is exported to a file as defined in the interface; the analysis of which in Excel is critically dependent on how the data is presented before it is exported. The results of the simulation were then gathered into one spreadsheet where a complete demand profile was calculated, the process for which can be found in Appendix 11.

The next stage in this methodology is the derivation of the formulas required to calculate the heat loads required by absorption chillers used to meet this profiled cooling demand.

4.2.5.2 Use of Waste Heat for Cooling – Calculations & Formula

The equation below is used as the foundation of the methodology used to quantify the heat load required to adequately power an absorption chiller for the purpose of meeting the cooling demand profile.

- Equation for Absorption Chiller COP

$$COP_{e-ABS} = COP_{ext}COP_{ABS} = \frac{\Delta H}{\Delta E}COP_{ABS}$$

Equation 4:6[6]

Where,

$COP_{e\text{-}ABS}$ = Electrical Equivalent COP of an Absorption Chiller

COP_{ext} = COP for heat extraction

COP_{ABS} = Absorption Chiller COP

ΔH = Heat extracted from turbine (W)

ΔE = Electricity that is lost (W)

- Substituting the following equation into Equation 4.14 above:

$$COP_{e-ABS} = \frac{Chilling\ Provided}{Electricity\ Lost}$$

Equation 4:7[7]

- Simplifies Equation 4.14 to:

$$\Delta H \times COP_{ABS} = Q_{Ch}$$

[6] (Harvey, 2006)
[7] (Harvey, 2006)

Equation 4:8[8]

Where,

Q_{Ch} = Amount of Chilling Provided (W)

This last equation (Eq. 4.16) can be rearranged to provide the equation that is necessary to calculate the heat demand of an absorption chiller in meeting the profiled cooling load, as shown below.

- Rearrange Eq. 4.16 for Heat Demand Formula:

$$\Delta H = \frac{Q_{Ch}}{COP_{ABS}}$$

Equation 4:9

This equation (4.17) can now be entered into the spreadsheet to calculate heat load from the cooling demand profiles. The process combining this calculation with the cooling data set and the resulting analysis can be found in Appendix 12.

To ensure accurate assessment of the use of absorption chillers in the energy network it is critical to subtract the cooling profile from the equivalent profile for heat available (represented by the electrical demand) in parallel with the inclusion of the heat required by the absorption chillers in the heat demand analysis for each phase. The cooling profile in this instance is representative of the electrical energy that would have been required to operate the conventional chillers, but that is instead being met by the waste heat.

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[8] (Harvey, 2006)

5 Results and Analysis

This chapter is dedicated to displaying the results of the various analytical methods applied throughout the course of this thesis, as defined in the Methodology section (4) above, alongside an explanation of the results shown. A brief analysis of each result set is also included at the end of the relevant section. The results of the calculations and data analysis performed as part of this investigation into the prospective University of Strathclyde energy network were as follows:

5.1 Load demand matching

This section outlines the results of the three, time stepped load demand matching analysis undertaken, as set out in the sections below.

5.1.1 Monthly Demand

The profile for the total monthly heat and power demand of the University of Strathclyde John Anderson Campus over the 2012-13 year, resulting from the analysis of the monthly demand for all combined phases, can be seen below in Figure 5:1.

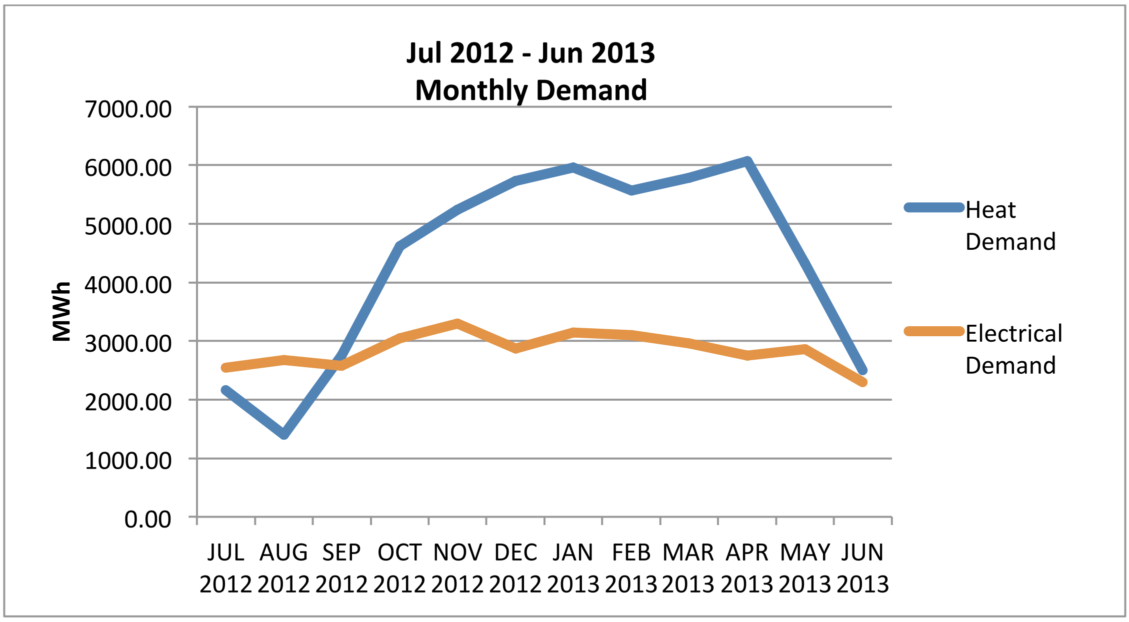

Figure 5:1 - Graph of Total Monthly Demand Loading

It can be seen in Figure 5:1 above that, even through this primary analysis of the campus energy usage, the total heat demand is around double the electrical demand for a large percentage of the year; with a peak heat demand of 6067MWh in April concurrent with an electrical load of 2567MWh, while the peak electrical load of 3295MWh in November is still significantly less than the heat demand of 5243MWh for that month. This would seem to indicate that a CHP system with a HPR of 1:1 might only be able to achieve around half of the total campus heat demand.

The graph also shows that in the summer months both July and August has lower heat than electrical demand; with the lowest heat demand found in August at 1400MWh matched by an electrical demand of 2674MWh. This lack of heat demand indicates the likelihood of waste heat generated for these months.

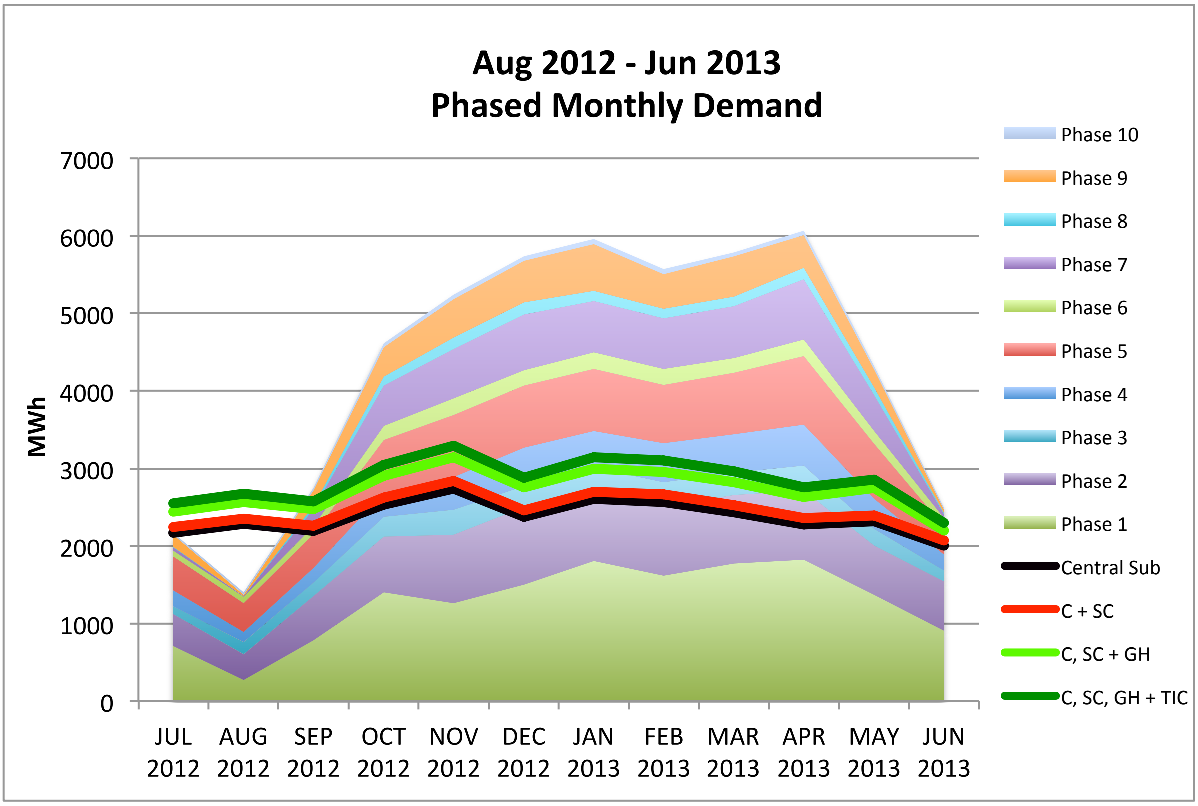

Figure 5:2 - Graph of Phased Monthly Campus Energy Loads – 2012-13

Figure 5:2 above shows the progression of the daily gas and electrical demand for each of the potential stages and phases of network expansion included in this analysis. The ten divisions of the stacked area of the graph signify the heat demand, with each profile labelled according to the development phase that it represents.

The four lines in the graph signify the monthly electrical load, also listed in order of electrical expansion Stages 1 to 4. Figure 5:2 shows that the heat generated by Stages 1&2 have the potential to meet the heat demand of Phase 1 and nearly all of Phase 2; missing the peak combined demand of Phases 1&2 at 2715 MWh for April with 2277 MWh and 2357 MWh of heat available from Stages 1&2 respectively.

It can also be seen in Figure 5:2 that the heat available in Stages 3&4 of the monthly data set is capable of meeting the full demand of Phases 1&2, while partially meeting the heat demand of Phases 3&4. The system is only unable to meet the demand of Phase 3 at its peak of 3040 MWh in April, with the heat available in this month only shown to be 2632 MWh and 2757 MWh for Stages 3&4 respectfully. The demand in Phase 4 of the heat network expansion is too great for the potential supply for the months of November through to May, also peaking at 3568 MWh for April.

Visual analysis of the monthly energy demands of the campus therefore suggests that the only viable options are Stages 3 or 4 of the electrical expansion combined with Phases 1 or 2 of the heating network.

The summed monthly phase data used in Figures 5:1 and 5:2 above can be found in located in Appendix 13. A graphical comparison of monthly demand for the full data set, including years 2010-2011 and 2011-2012, can be found in Appendix 14.

With 16 results sets for the HPR analysis is was not practical to include all of the results in the main body of the report. Therefore, the three data sets found to have the most appropriate ratios for each Stage in the analysis, Phases 2,3 and 4 of the heating network in each case, are defined in Table 5:1 and Figure 5:3 below. The full results and summary for the monthly analysis can be seen in Appendices 15, 16 and 17.

Table 5:1 - Monthly HPR Summary

	Monthly Heat to Power Ratios - Best Matches											
	Electrical - Stage 1			Electrical - Stage2			Electrical - Stage 3			Electrical - Stage 4		
	HP2	HP3	HP4	HP2	HP3	HP4	HP2	HP3	HP4	HP2	HP3	HP4
MAX	1.192	1.335	1.567	1.152	1.289	1.514	1.031	1.155	1.356	0.985	1.103	1.294
MIN	0.265	0.334	0.390	0.257	0.324	0.378	0.236	0.297	0.347	0.226	0.285	0.333
MEAN	0.833	0.933	1.083	0.805	0.902	1.047	0.726	0.813	0.944	0.694	0.777	0.902

The yellow highlighted cells in Table 5:1 above show the closest values in the data set to the ideal for each of the maximum, minimum and mean results for the selected network arrangements. As these most ideal results do not all fall on the one network combination, selecting the best matched arrangement is a process of assessing which value is most important to the energy network bring proposed.

In this analysis the key value was taken to be the maximum demand, and as such the results shown in Figure 5:1 indicate that the three best matched HPR for the energy network would be Stage 3 & Phase 1 or Stage 4 with Phases 2 or 3. Of these three, the most appropriate system would appear to be Stage 4 of the electrical expansion with Phase 2 of the heating network where the maximum heat demand value is met by the supply and the percentage of heat used is just under 70% on average. These three best matched HPR from the monthly data set can be seen below in Figure 5:3.

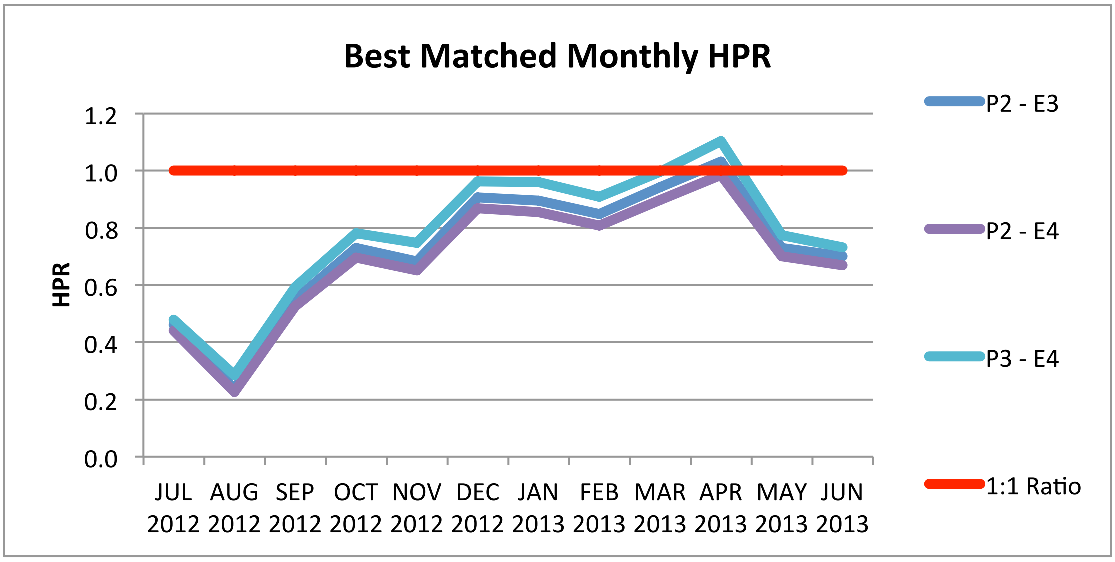

Figure 5:3 – Graph of Monthly HPR Summary

It must be noted that the HPR for Phase 1 of the heating network were consistently below 1 for each of the electrical Stages; however, these results were excluded from the best matched results sets, as shown in Table 5:1 above, due to their low average heat demand.

5.1.2 Daily Demand

The profile for the total daily heat and power demand of the University of Strathclyde John Anderson Campus from the 19th of December 2012 up to the 30th of June 2013, resulting from the analysis of the half-hourly demand for all combined phases, can be seen below in Figure 5:4.

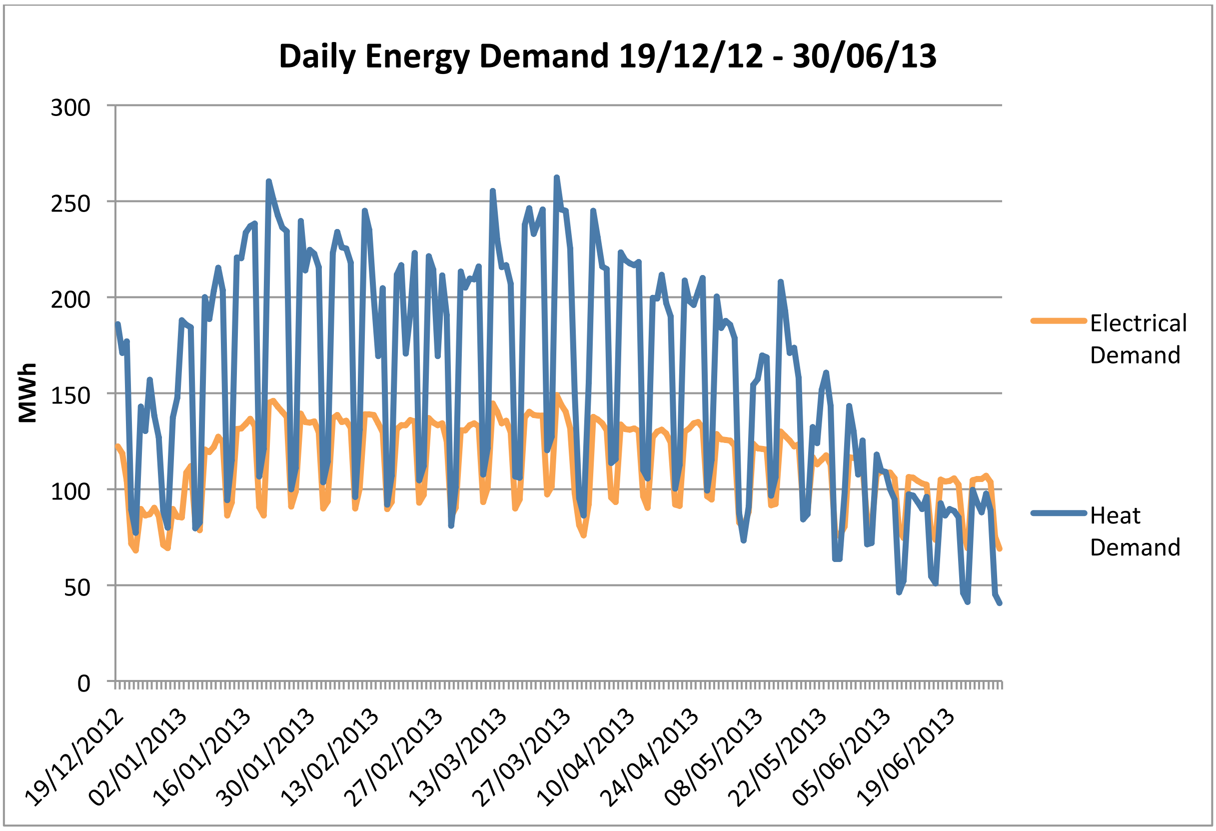

Figure 5:4 - Daily Energy Demand Loads

The impact of the shorter time steps can be clearly seen when comparing Figure 5:4 above with the monthly equivelant in Figure 5:1 in the previous section. The peak loads for both heat demand and electrical loads are both significantly lower, at 262 MWh and 149 MWh respectully with both occuring on 25/03/13. This signifies that the heat demand is still roughly double the heat available for periods of the analysis, in agreement with the results of the monthly load demand analysis above.

The graph in Figure 5:4 also shows that both the heat and electrical demand peak and trough concurrently, indicating a consistent synchronicity between the two profiles over the course of the analysis. It can also be seen that, unlike the results of the monthly analysis above, electrical demand throughout June surpasses the heat demand; although, the peak electrical demand of 109 MWh is still lower than the peak of 117 MWh heat demand.

Due to the scale of the daily data and for practicallity the Phased data set for the daily timestep analsis set has been inlcuded in Appendix 18. Therefore, for the purpose of illustrating the interaction between the proposed stages of network expansion, the daily demand for January 2013 is shown in Figure 5:5 below .

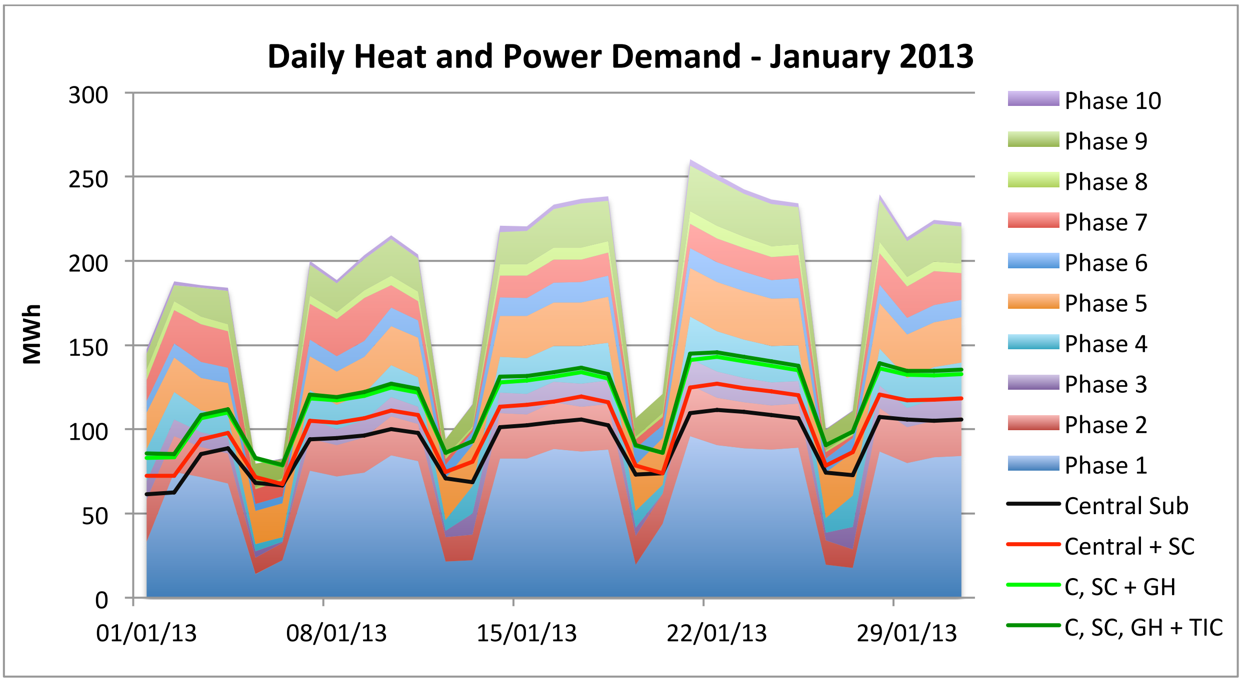

Figure 5:5 – Graph of Phased Daily Campus Energy Loads - January 2013

Figure 5:5 above shows the progression of the daily gas and electrical demand for each of the potential phases of network expansion included in this analysis over the month of January. As shown above and in Appendix 18, the scale of the data entered into the graph is now becoming inhibitive to the analysis carried. Graphical representation therefore starts to become more of an illustrative and less of an analytical tool for the purposes of this analysis.

What can be seen in both Figures 5:5 and in Appendix 18 however, is that the daily heat demand is roughly concurrent with the demand pattern established in the monthly data set analysis in the section above; the heat available from electrical demand Stage 2 appears able to meet the heat demand of Phases 1&2, peaking on the 25th of June at 98 MWh and 128 MWh respectfully with 129 MWh heat available for that day.

Although it can also be seen in Figure 5:5 that the heat available from Stage 1 of the proposed electrical network is not capable of meeting the demand from even Phase 1 of the heating network, highlighted above in Figure 5:5 and also shown in Appendix 18. This is in contrast to the results of the monthly analysis, illustrating the dangers posed by reliance on the analysis of high-level data alone.

Again due to the scale of the data set it was not practical to present the calculated HPR values for each profile in either graphical or tabular form. The demand profiles found to have the best-matched ratios for each potential phase of the energy network included in this analysis are therefore summarised in Table 5:2 and Figure 5:7 below. The graphs and tables representing daily HPR for each network combination can be found in Appendix 19 and 20.

Table 5:2 - Best Matched Daily Energy Network HPR

	Best Matched Daily HPR		
Electrical Stage:	3 - (C, SC & Graham Hills)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	0.8949	**1.1531**	**1.2703**
MIN	0.0828	**0.2004**	**0.2196**
MEAN	0.4457	**0.6190**	**0.7031**
Electrical Stage:	4 - (C, SC, GH & TIC Building)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	0.8727	**1.1245**	**1.2388**
MIN	0.0817	**0.1982**	**0.2196**
MEAN	0.4379	**0.6085**	**0.6912**

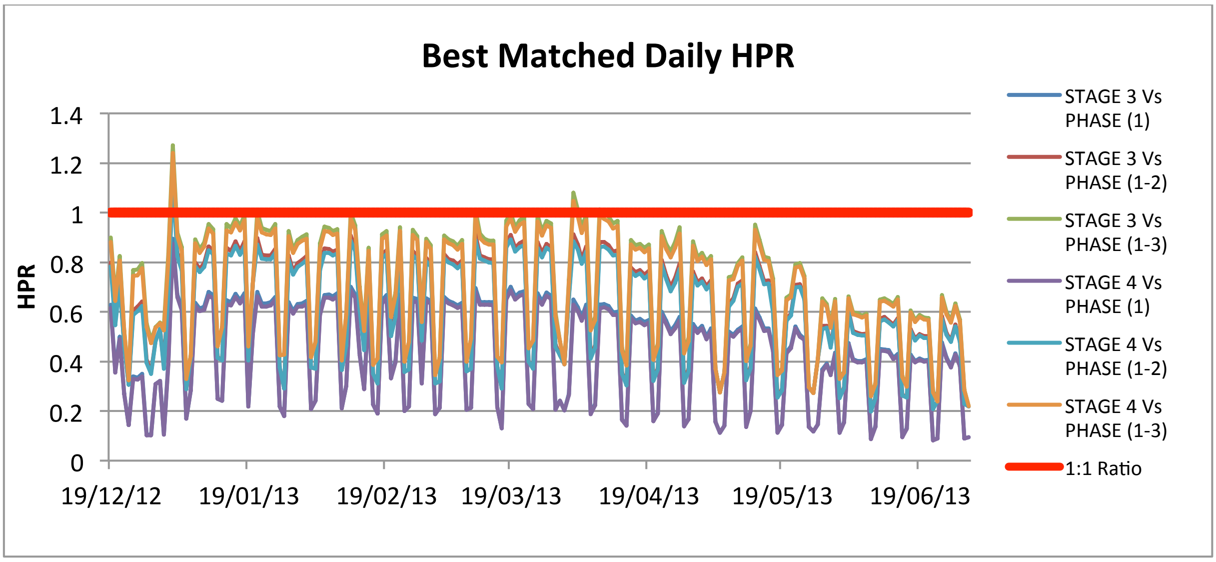

Figure 5:6 – Graph of Best Matched Daily HPR

The cells highlighted in yellow for Table 5:2 above show the closest values in the data set to the desired maximum result for the selected network arrangements. In the analysis of the daily data set, these results represented the only network combinations with a maximum HPR that indicated the heat demand could be met by the system. The maximum value shown for these two network variations would indicate a good match to the system however the low minimum and average indicate that this may not be the case. This is where the illustrative properties of graphical analysis can be used to great effect; as seen in Figure 5:6, Phase 1 for both Stages 3&4 represent very low percentage heat use and therefore low system efficiency while Phases 3&4 for these stages are much better matched to the system demands.

The excess heat demands shown for these network arrangements in Table 5:2 could possibly be met by other means for the few occasions per year that the system cannot meet the demand directly. This result therefore highlights the potential for the implementation of peak heat load shifting in the system for these system arrangements and others with similar potential, as seen in the full HPR table located in Appendix 19.

Without the use of heat storage, the results of the daily demand loading analysis indicate that the only two viable variations of the energy network are through Stages 3 and 4 of the electrical network expansion combined with Phase 1 of the heating network. Stage 3 with Phase 1 is the preferable network variation as it has the highest minimum and average demand of these two options, indicating greater efficiency.

However, if heat storage is found to be feasible to the extent that the peak demand of 3&4 for these same Stages can be met, then the best matched network variation would contain either the Phase 2 or Phase 3 heating networks with Stage 3 expanded electrical network. Of these two, the most appropriate system would appear to be Stage 3 of the electrical expansion with Phase 3 of the heating network where the percentage of heat used is just over 70% on average.

If the heat storage is feasible but cannot match the 27% additional heat demand to the level produced required to make the Stage 3 with Phase 3 network variant a viable option then the best matched alternative is Stage 4 with Phase 2; this has the lowest additional peak of the best-matched variants and also has an average heat used is more that 60% of what is produced.

Additionally, the maximum HPR for the same three Phases of the energy system, but without considering the expansion of the electrical network to Stages 3&4, can be seen to increase by around 33%. This increased maximum is also shown to occur concurrently with an increase in the frequency of instances where the heat demand surpasses availability, as illustrated in Table 5.3 and Figure 5.7 below.

Table 5:3 - Limited Electrical Network HPR Summary

	Limited Electrical Network – Daily HPR Summary		
Electrical Phase:	1 - (Central Substation)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	1.1883	1.5311	1.6868
MIN	0.1001	0.2424	0.2472
MEAN	0.5573	0.7738	0.8796
Electrical Phase:	2 - (C & Sports Centre)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	1.0282	1.3248	1.4596
MIN	0.0924	0.2258	0.2472
MEAN	0.5003	0.6956	0.7900

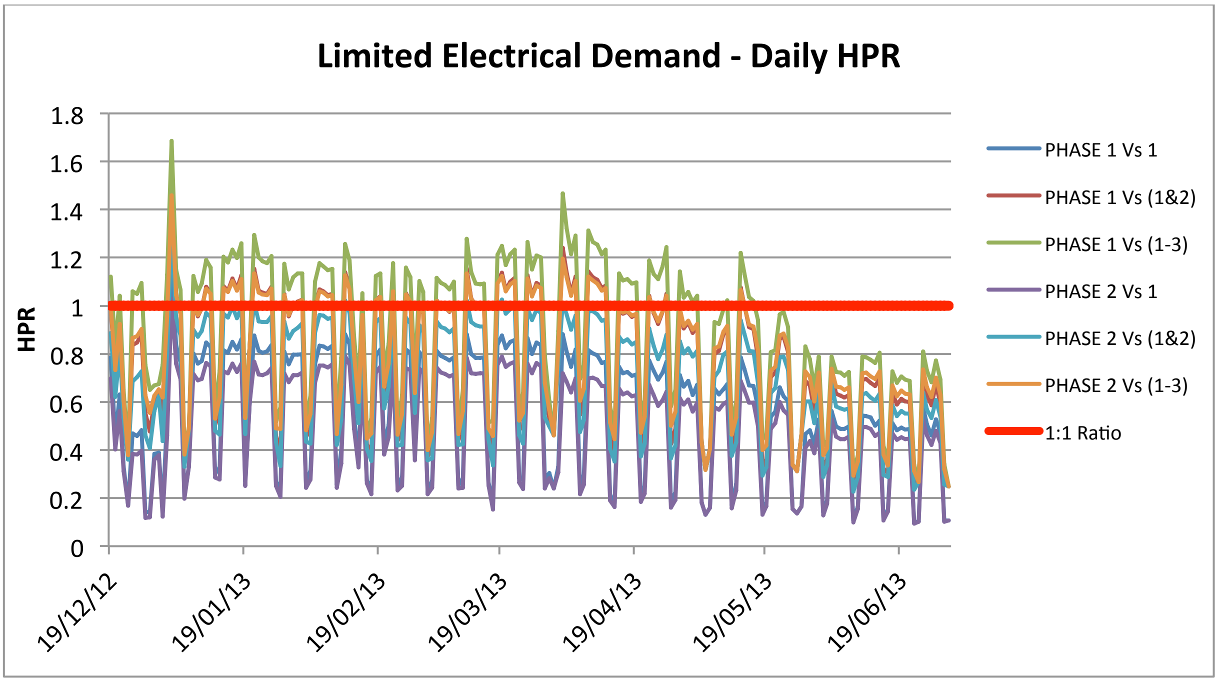

Figure 5:7 - Graph of HPR for Limited Electrical Demand

The results shown in Table 5:3 and Figure 5:7 therefore strongly indicate that, according to analysis of the Daily demand data, Stages 1&2 of the electrical network expansion are not at all viable without the use of heat demand shifting.

5.1.3 Half-hourly Demand

In this analysis the scale of the half-hourly data set made the presentation of demand profiles for the entire period of analysis impractical. Therefore, the total half-hourly heat and power demand profile is illustrated through the total recorded demand profiles for the month of January 2013, as can be seen below in Figure 5:4. Complete half-hourly demand profiling for the full period of analysis is shown, also on a monthly basis, in Appendix 21.

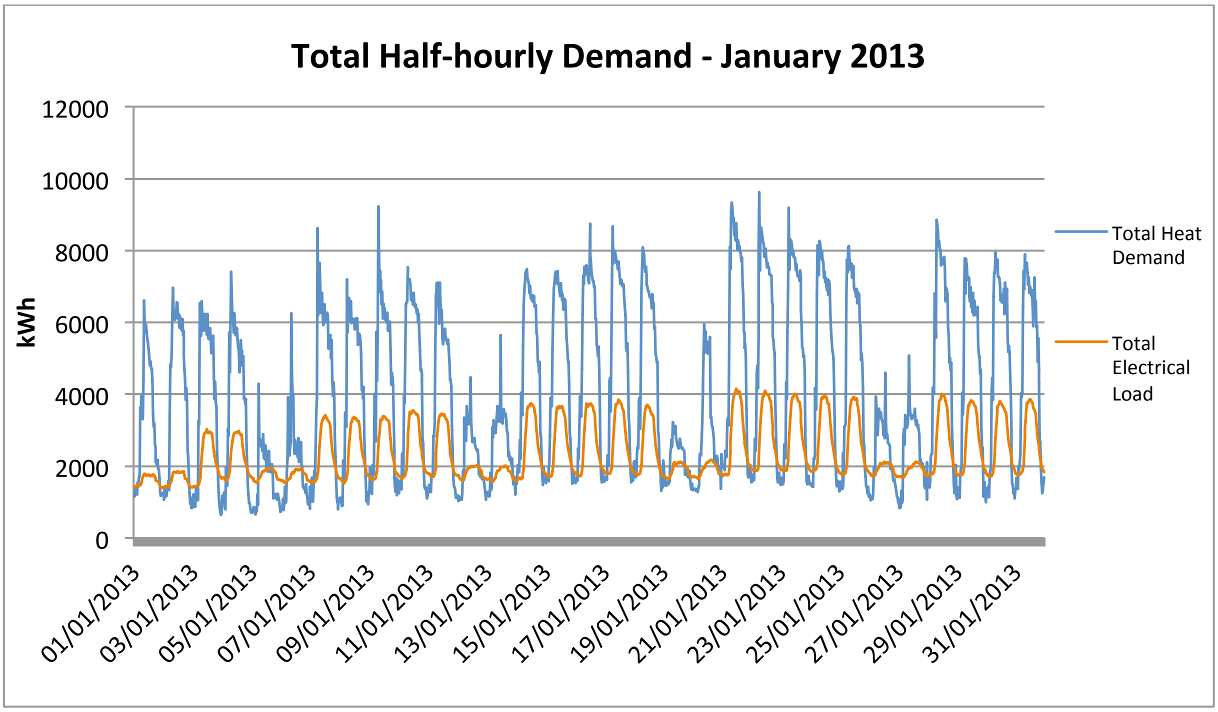

Figure 5:8 – Total Half-hourly Demand for January 2013

As seen in the daily demand analysis, Figure 5:8 above shows that both electrical and heat demand follow a similar profile throughout the analysis. The maximum total heat demand for the month of January is 9.6 MWh, while the maximum heat available (electrical load) is 4.1 MWh; the maximum values seen throughout the complete analysis are 10.2 MWh and 4.3 MWh for heat demand and availability respectively.

To more clearly illustrate the interaction between the two total demand profiles when using half-hourly data, Figure 5:9 below shows the electrical and heat over the first week in January. This week was selected purely to illustrate the variation of the profiles over this timeframe; the University is technically shut down for this week of the year however the variation in both head and power demand is still clear to see. At this scale it can be seen that, although both data sets remain true to the anticipated weekly profile seen in Figure 5:8 above, the total heat demand is in constant fluctuation while the electrical demand remains relatively steady.

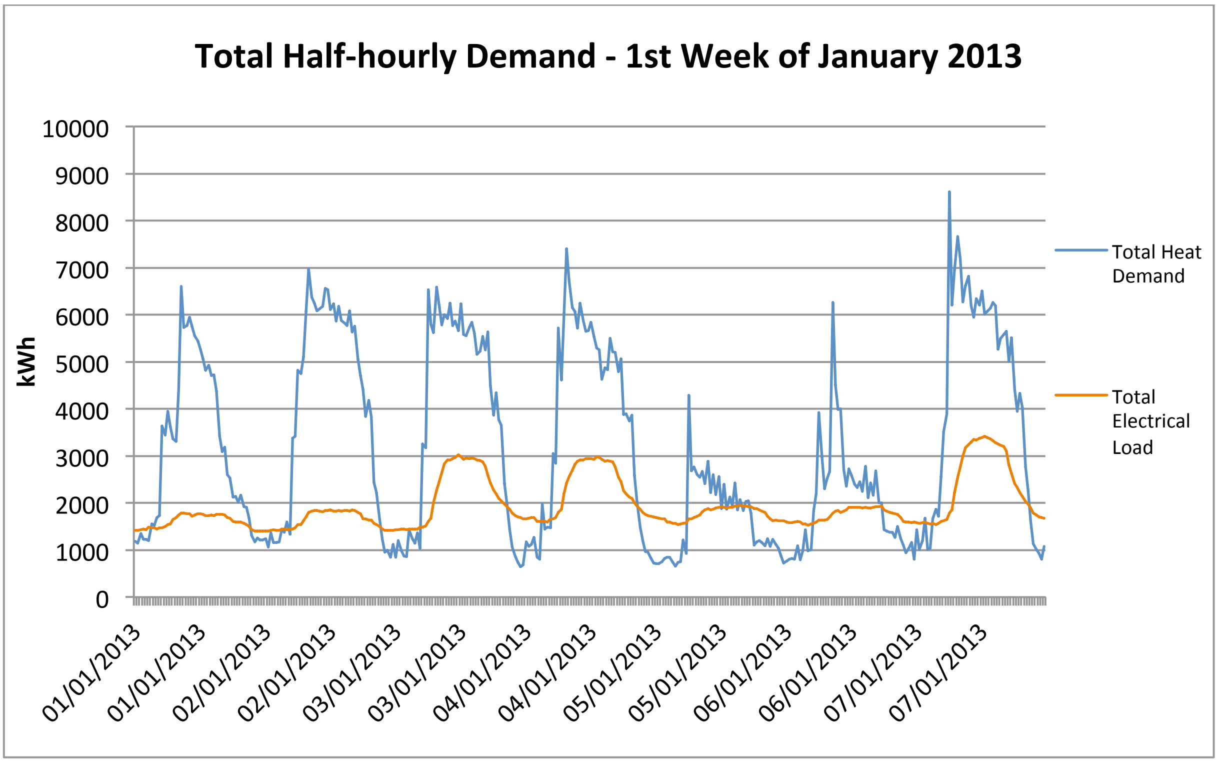

Figure 5:9 – Total Half-hourly Demand for the 1st Week in January 2013

The division of this total half-hourly demand into the proposed energy network is shown in Figures 5:10 and 5:11 below, again with the electrical load profiles representing the heat generated and therefore available to the system. As with the presentation of the total demand in Figures 5:8 and 5:9 above, the scale of the half-hourly data set means that graphical illustration is very limited in its scope for analysis unless it is scaled to a degree that allows the interaction of the profiles to be seen; this is illustrated in Figures 5:10 and 5:11, which show the resulting phased profiles for all the proposed network variations over the assessed portion of the month of December and then for the day of the 21st of December respectfully. The month of December was chosen to represent the phases due to the limited size of the December data, which allows for a clearer representation; again the University is technically not operational for this month however the large variations in demand can still clearly be seen.

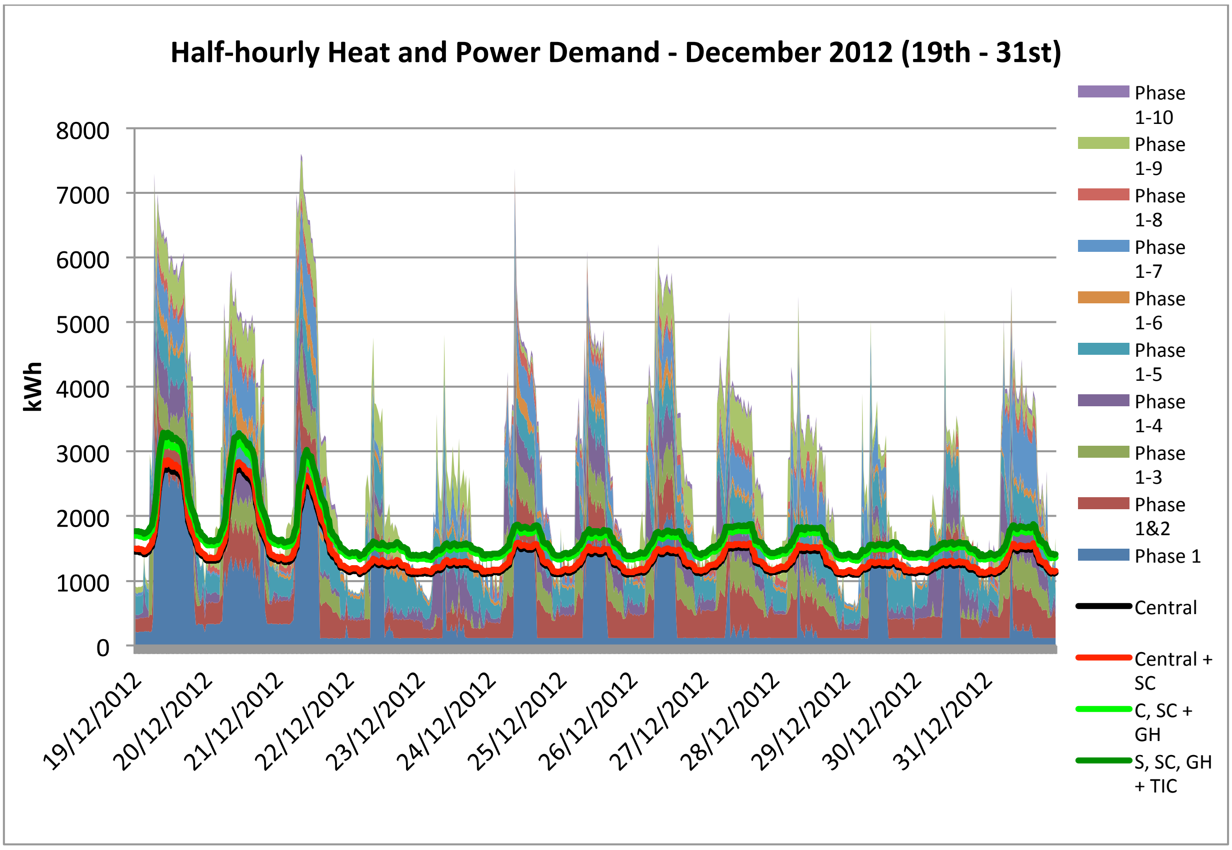

Figure 5:10 – Phased Half-hourly profiles: December 2012

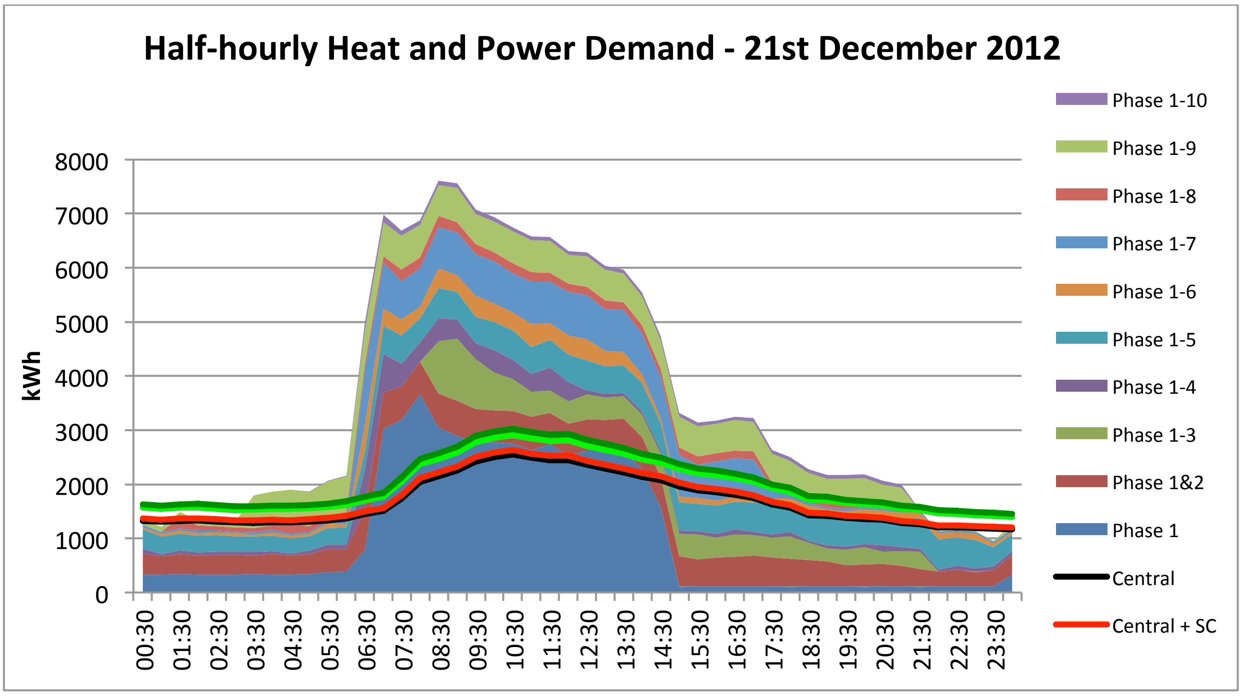

Figure 5:11– Phased Half-hourly profiles: 21st of December 2012

As can be seen above, the results shown in Figure 5:10 present a defined outline of each profile although the interaction shown is slightly limited due to the scale of the graph. Alternatively, the results shown in Figure 5:11 are clearly limited by the finer scale applied but the network interactions are well defined. The results of the two graphs, in combination with analysis of the complete data set as presented in Appendix 21, show that not one of the electrical expansion Stages can continually match the heat load of the campus; this is highlighted in Figure 5:11 above. On the day illustrated in this graph (21st December 2012) the peak heat demand for Phase 1 of the network expansion is shown to be 3.6 MWh while the maximum heat available is 3 MWh; there is not enough heat generated through any Stage of the electrical expansion to sustain Phase 1 of the district heating network. This result is in contrast to both of the previous analysis for the alternative time steps, which both showed that each potential Stage of the electrical network expansion would generate enough heat to meet at least Phase 1 of the heat demand. This also demonstrates the analytical benefit achieved through the use of data recorded over short time steps.

Interestingly, although this is assessment focuses on the energy demand matching on the campus site and the selection of the dates illustrated in Figures 5:9-11 are simply illustrative of this, the impact of the University closure over the last weeks in December and first few in January had little apparent impact on the energy demand profile; as can be seen through comparison of the graphs shown in Appendix 21.

As with the daily data analysis above, due to the scale of the data set it was not practical to present the full, calculated HPR values for each profile in either graphical or tabular form. With the half-hourly data, the results sets were 48 times larger than those for the daily analysis and the fluctuation in heat demand between time steps, as illustrated in Figure 5:9 above, was continuous throughout. This combination essentially prevented any meaningful analysis of the half-hourly HPR results when presented in graphical form in any scale other than over a 24-hour period.

The summarised results of the best matched half-hourly HPR analysis can be seen below in Table 5:4, the full summary can be seen in Appendix 22. The table shows the most appropriate network combinations for each Stage of electrical expansion and that, when applying the same analytical methods to the half-hourly demand data set as was applied to the daily and monthly data, none of these combinations are calculated as being viable.

Table 5:4 – Best Matched Daily HPR Results

	Best Matched HH HPR		
Electrical Stage:	1 - (Central Substation)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	3.2765	3.6657	4.0020
MIN	0.0000	0.0000	0.0000
MEAN	0.4936	0.7214	0.8245
Electrical Stage:	2 - (C & Sports Centre)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	3.1762	3.5535	3.8795
MIN	0.0000	0.0000	0.0000
MEAN	0.4785	0.6994	0.7992
Electrical Stage:	3 - (C, SC & Graham Hills)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	2.7823	**3.1129**	**3.3984**
MIN	0.0000	**0.0000**	**0.0000**
MEAN	0.4235	**0.6171**	**0.7048**
Electrical Stage:	4 - (C, SC, GH & TIC Building)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	2.6717	**2.9891**	**3.2632**
MIN	0.0000	**0.0000**	**0.0000**
MEAN	0.4065	**0.5924**	**0.6766**

The cells highlighted in yellow for Table 5:4 above show the closest values in the data set to the desired maximum result for the selected network arrangements; as shown in Table 5:4, even the lowest of these results is over twice the maximum heat available from the network. This indicates that, according to the half-hourly HPR results, the maximum demand for each proposed Phase of the energy network has a maximum demand greater than any of the Stages of heat generation can achieve and therefore none of the analysed network variations is capable of consistently meeting the heat demand required by the campus. To illustrate the variation of the HPR for each time step in the analysis at a monthly and daily scale, the results for Phases 2&3 of the energy network in combination with Stages 3&4 of the electrical expansion are shown in Figures 5:12 and 5:13 below; these results sets were chosen for their relatively low maximum and appropriate mean values, thereby representing the best matched results from the half-hourly analysis.

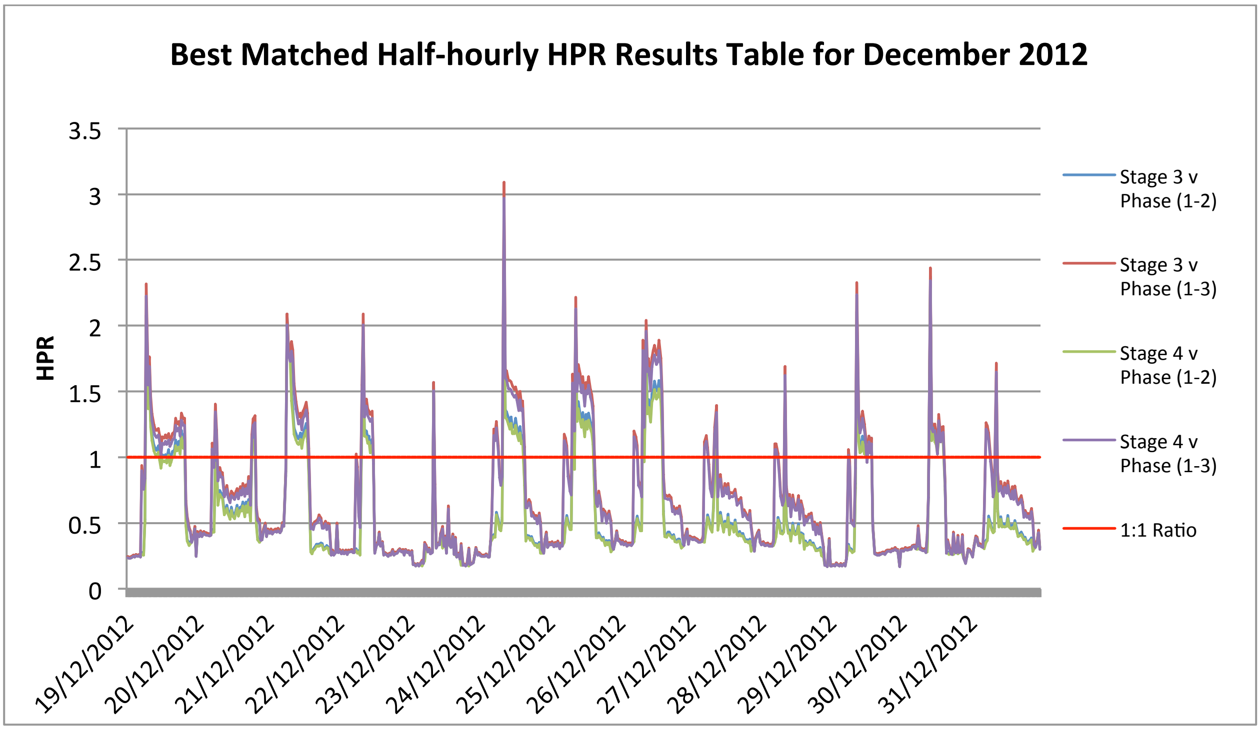

Figure 5:12 – Best Matched Half-hourly HPR for December 2012

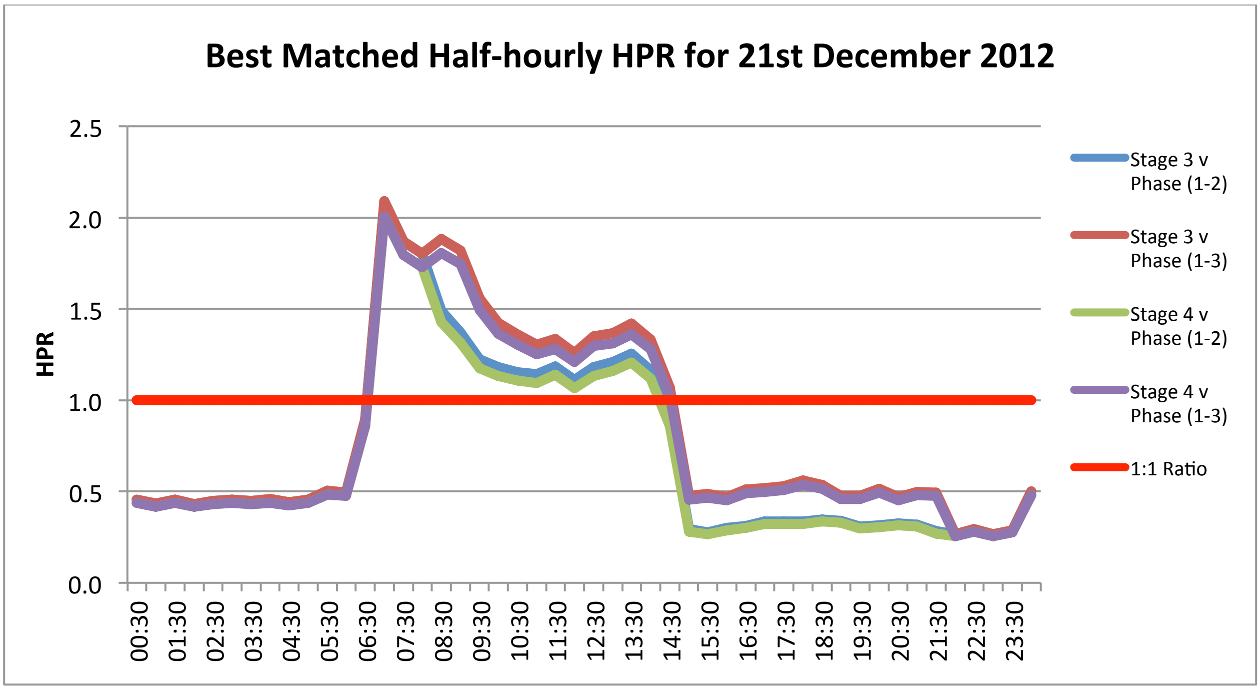

Figure 5:13 - Best Matched Half-hourly HPR for 21st December 2012

The results illustrated in Figures 5:12 and 5:13 above clearly support the results shown in Table 5:4, with the HPR calculated for even the best matched network variations shown to breach the ideal maximum 1:1 ratio on at least one occasion through the month. The results shown in Figure 5:13 in particular illustrate that the HPR on the 21st of December 2012 is greater than this ideal maximum for around 9 hours throughout the day. The HPR results for the 21st of December can be seen in Appendix 23.

The results of the half-hourly analysis show clearly that none of the proposed network combinations included in this analysis are viable options for the energy network as the heat demand cannot consistently be met by the heat available from the system in any of the variations.

However, the results also show that from half-hour to half-hour there is a large variation between heat demand and supply in the network. However, the scale of this variation in demand between concurrent time-steps may indicate that the network could be achievable through the application of peak demand shifting through heat storage.

5.1.4 Results Summary

This section sets out the results of the analysis in the preceding section (5.1) in Table 5:5 below.

Table 5:5 - Demand Load Matching Results Summary

	Best Matched Network Combination		
Time step	Monthly	Daily[9]	Half-hourly[10]
Stage	4	3	4
Phase	2	1	1

[9] This Daily combination is the best possible match according to the analysis when there is no peak heat load shifting available through heat storage.
[10] As no half-hourly result was viable in the analysis, this selection represents the nearest viable network combination as it has the lowest maximum HPR value as shown in Table 5:4 above.

The pattern formed from the results of each time step analysis, collected in Table 5:5 above, indicates that for the energy network to be viable a larger electrical network expansion Stage is required generate enough heat to meet the demand of the more limited heat network Phase proposals.

5.2 Comparison of Results Sets

This section outlines the impact on the results of the above analysis through the use of half-hourly data alone, with the HPR calculated for this data set averaged over the broader daily and monthly time steps.

The results of the half-hourly HPR, averaged for each day in the analysis, can be seen summarised in Table 5:6 below. These were calculated in order assess the similarity, and therefore also the quality, of the results for each analytical time step shown in Section 5.1 above. The full table for the summarised, average daily HPR for each network combination can be found in Appendix 24.

Table 5:6 – Averaged Daily HPR from Half-hourly Data

	Half-hourly HPR Averaged to Daily		
Electrical Stage:	3 - (C, SC & Graham Hills)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	0.9159	1.1970	1.3731
MIN	0.0871	0.2081	0.2128
MEAN	0.4235	0.6171	0.7048
Electrical Stage:	4 - (C, SC, GH & TIC Building)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
MAX	0.8800	1.1501	1.3193
MIN	0.0836	0.1998	0.2042
MEAN	0.4065	0.5924	0.6766

It clear through comparison of the results shown in Table 5:6 with those in Table 5:4 above that, by averaging the half-hourly HPR, the maximum values resulting from the half-hourly analysis become significantly lower; even to the extent that Phase 1 of the network becomes a viable network arrangement for Stages 3&4 of the electrical expansion.

This is in direct contrast to the results of the half-hourly analysis, which indicated that none of the options were viable. Similarly, the averaged minimum values are significantly higher in Table 5:5 than those resulting from the direct half-hourly data, shown in Figure 5:4, which would suggest a lower degree of wasted heat for the system. The values calculated for the averaged data are seen to be identical to those shown for the half-hourly results; this was to be expected as the results are based upon the same data set.

Figure 5:14 below shows the best matched averaged data for December 2012, facilitating a direct comparison with the original half-hourly results shown above in Figure 5:12.

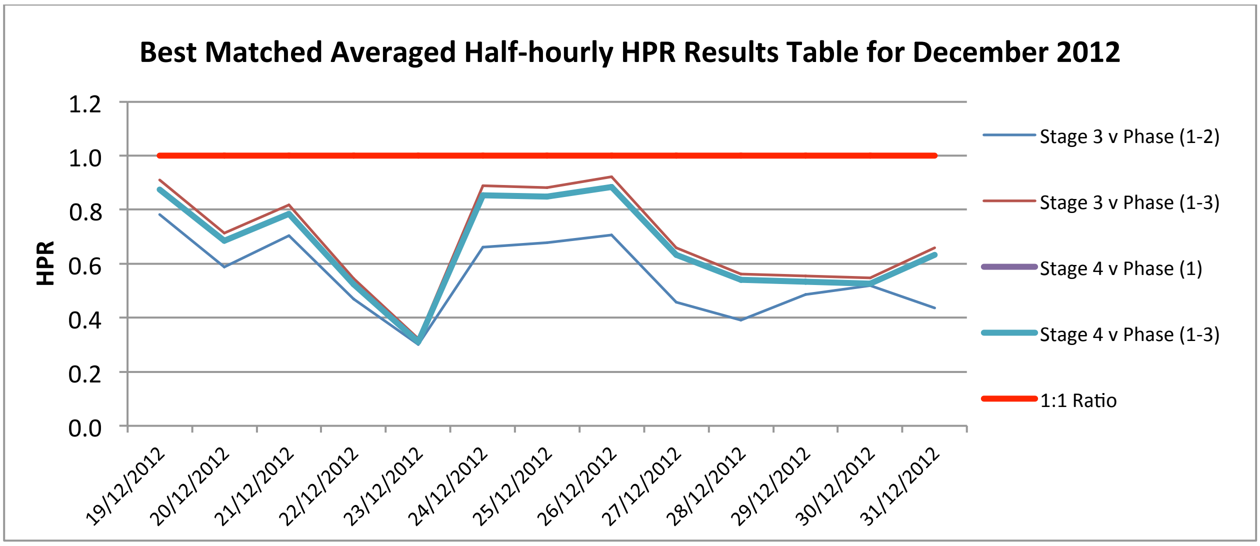

Figure 5:14 - Averaged HPR for Best Matched Half-hourly Data - 21st December

The averaged data, as expected, is significantly less variable the results are therefore also much more clearer. Unlike the original results shown in Figure 5:12, each of the network options illustrated is shown to be a viable network option in Figure 5:14.

These differences between the results of the half-hourly analysis and the data set averaged from these results set are reinforced by the contrast between the best-matched network variations selected from the half-hourly data on the 21st of December, a shown in Figure 5:13 above, and the average values for these network variations for the same day, as shown in Table 5:7 below.

Table 5:7 – Averaged Daily HPR for Best Matched Half-hourly Network Variations on the 21st of December 2012

	Average HH HPR	
Network Variation	PHASE 1 - 2	PHASE 1 - 3
Stage 1	0.703	0.818
Stage 2	0.675	0.785

While the graph in Figure 5:13 indicates that none of the variations are viable, Table 5:6 shows that when the HPR are averaged each becomes a potential network option as the extreme fluctuations seen in the half-hourly demand data of each time step even out to produce a more acceptable result.

The variation between the results of the half-hourly analysis and those achieved through the daily average calculated from these results highlights the variety of conclusions that can be drawn from alternative analysis of the same data set.

Figure 5:15 below shows the half-hourly HPR, averaged for each day in the analysis and presented over the full period of analysis for direct comparison with the daily results shown in Figure 5:6 above.

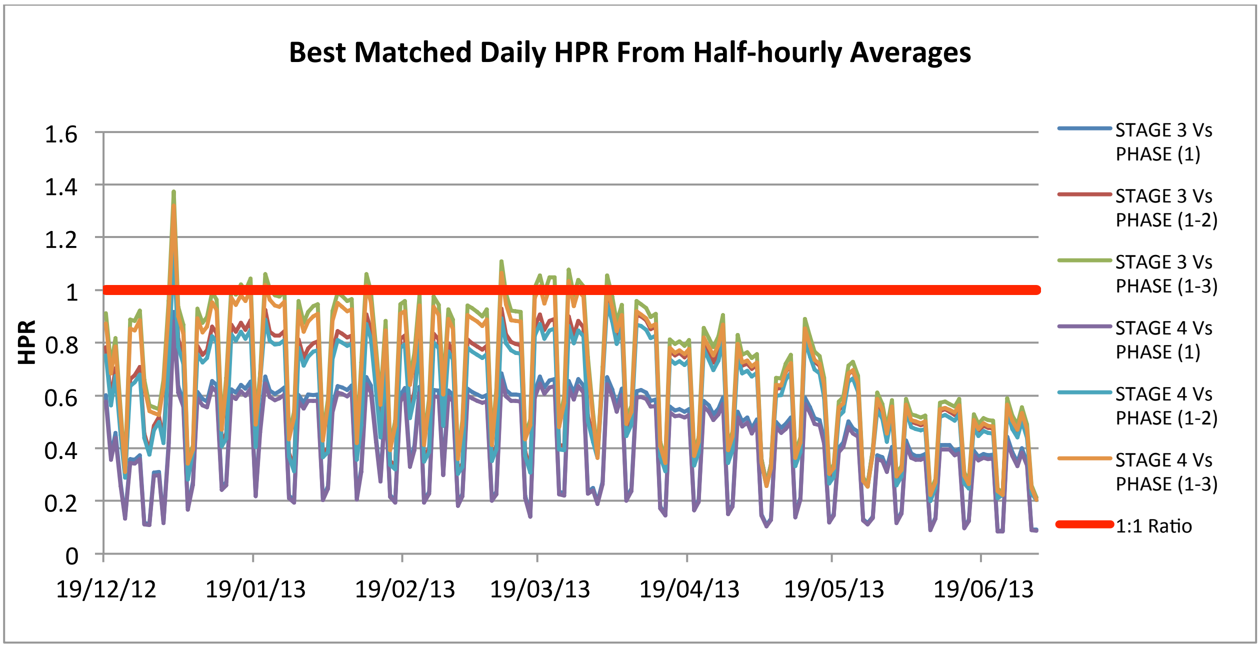

Figure 5:15 - Averaged Daily HPR for Best Matched Half-hourly Data

Comparing the averaged half-hourly results shown in Figure 5:15 and Table 5:6 with the results achieved through the daily analysis, shown in Figure 5:6 and Table 5:2, highlights slight variances between the two results sets. It is worth noting that while both data sets were both constructed from the half-hourly data the HPR results shown in Table 5:2 were calculated using the total daily demand while those in 5:5 represent the average of the HPRs calculated for each half-hourly time step.

Analysis of both results sets shows that they offer the same conclusions for the most appropriate network combinations and the average HPRs are also very similar; however, the maximum demand values are also shown to be higher for the averaged data and Figure 5:15 shows that Phase 3 for Stages 3&4 in this results set breaches the ideal 1:1 ratio on more occasions than the original daily analysis shown in Figure 5:6.

Overall, while there are some small variations in the results of the two daily analysis methods, the results are concurrent on the important issues being assessed in that the best matched network combination is shown to be the same for both daily results sets; Stage 3 with Phase 1 as a stand alone system and Stage 3 with Phase 3 if appropriate heat demand shifting is available.

The results of applying these results, calculated as an average HPR for each month in the half-hourly analysis, across a monthly timeframe can be seen summarised below in Table 5:8. The best-matched network combinations have been highlighted in green and the most appropriate results for the maximum, minimum and mean highlighted in yellow. The full table for the summarised, average monthly HPR for each network combination can be found in Appendix 25.

Table 5:8 – Summary of Monthly HPR from Averaged Half-hourly Data

	Half-Hourly Data - Monthly Averaged Profiles											
	Electrical - Stage 1			Electrical - Stage 2			Electrical - Stage 3			Electrical - Stage 4		
	HP2	HP3	HP4	HP2	HP3	HP4	HP2	HP3	HP4	HP2	HP3	HP4
MAX	0.86	**1.013**	1.2	0.833	**0.982**	1.163	0.73	0.86	**1.018**	0.701	0.826	**0.977**
MIN	0.483	**0.514**	0.608	0.468	**0.498**	0.59	0.421	0.448	**0.53**	0.404	0.429	**0.508**
MEAN	0.715	**0.823**	0.994	0.693	**0.798**	0.964	0.611	0.703	**0.848**	0.586	0.675	**0.814**

The results shown above in Table 5:8, when compared to the results of the original monthly analysis as presented in Table 5:1, show an overall decrease in the maximum HPR value for each network combination. In the original monthly analysis, which used the manually recorded monthly demand data set, the only viable network combination that allowed expansion beyond Phase 1 was shown to be Stage 4 with Phase 2. In Table 5:8 above this has increased to include Phases 2&3 for Stages 2&3 along with Phases 3&4 for Stage 4. The averaged result set also shows an increased minimum value for the HPR, which indicates lower losses from the system although the average HPR is also shown to be lower and so the losses may in fact be greater overall. This is more clearly assessed through graphical representation of the best-matched results, as shown below in Figure 5:16.

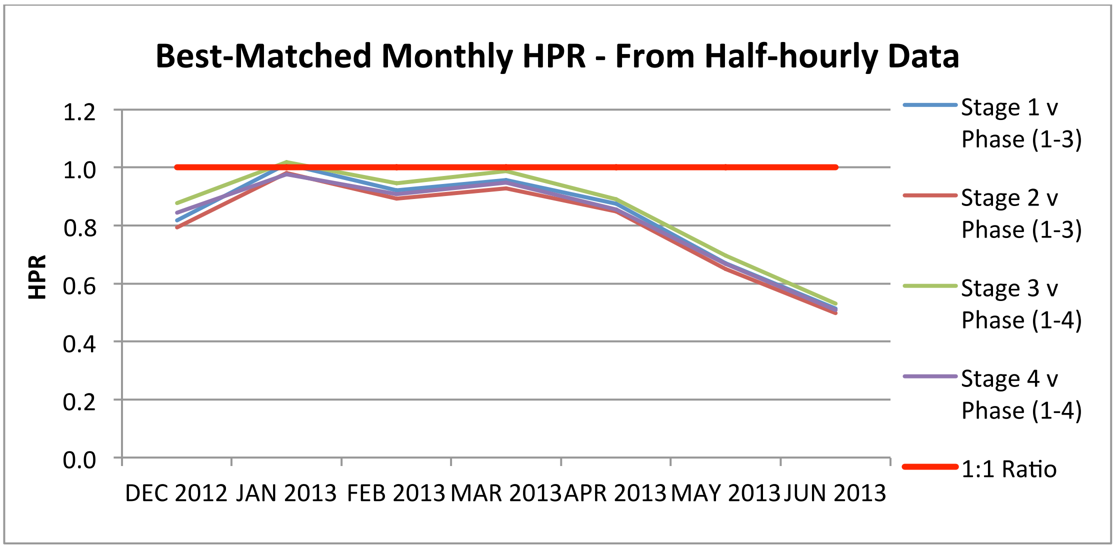

Figure 5:16 - Graph of Best-matched Monthly HPR from Half-hourly Data

It becomes clear when viewing Figure 5:16 alongside the original monthly results set, seen in Figure 5:3, that the comparison is slightly limited due to the restrictions placed on the analysis by the availability of half-hourly data. It can also be seen that the peak for both heat and electrical demand shown in April of the original monthly analysis is not present in the averaged data result set where the peak value is shown to be in January. This shift of peak demand is more in line with that which would be expected, due to anticipated high levels of energy use through the cold weather combined with the student exam period; suggesting that the averaged results set is possibly more in line with the expected energy use than the manually recorded data set. The results sets do however, other than this shifted peak value, follow the same pattern, which indicates an agreement on the demand profile for both heat and electrical demand even though the actual resultant values for each are different.

According to this analysis of the monthly results set, based upon averaged half-hourly HPR results, the best-matched energy network combination is Stage 4 with Phase 4; this combination is the most expansive result achieved in any of the preceding analyses and represents the most appropriate maximum, minimum and average values in this results set. It must also be said that the combination of Stage 2 with Phase 3 comes very close to matching the potential shown for this best-matched stag, while Stage 3 in combination with Phase 4 actually shows more appropriate values but is limited by its maximum being over 1 and so would only be viable through the application of peak heat load shifting.

5.2.1 Results Summary

This section sets out the results of the analysis in the preceding sections (5.1 and 5.2) in Table 5:5 below.

Table 5:9 - Demand Load Matching Results Summary

	Best Matched Network Combination				
Time step	Monthly	Daily[11]	Half-hourly[12]	**Monthly (AV)**	**Daily (AV)**
Stage	4	3	4	4	3
Phase	2	1	1	4	1

The pattern formed from the combined results of each time step analysis, collected in Table 5:9 above and including the results sets achieved through the averaged half hourly HPR data, shows the results achieved through both methods are in agreement in indicating that for the energy network to be viable a larger electrical network expansion Stage is required to generate enough heat to meet the demand of the more limited heat network Phase proposals. The exception to this pattern is the monthly results set based upon the averaged half-hourly HPR data, for which the best-matched network combination included a more expansive, viable heat network. This is possibly an indication that the by spreading the load demand matching through the use of peak heat load shifting, more network variations may become feasible.

5.3 Heat demand Shifting

This section outlines the results of the heat demand shifting analysis undertaken, as set out in the sections below.

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[11] This Daily combination is the best possible match according to the analysis when there is no peak heat load shifting available through heat storage.

[12] As no half-hourly result was viable in the analysis, this selection represents the nearest viable network combination as it has the lowest maximum HPR value as shown in Table 5:4 above.

5.3.1 Demand Matching through Heat Storage

The results of the analysis into the availability of heat for each network combination are shown below in Table 5:9. The total heat availability throughout the analysis can be seen graphically represented for each month in Appendix 26, with the complete summary table arrayed in Appendix 27.

Table 5:10 –Heat Storage Energy Balance across Viable Phases

		Summary of Phased Available Heat (kWh)			
		Phase 1	Phase 1-2	Phase 1-3	Phase 1-4
Stage 1	Max	68240.08	48596.38	47150.54	43333.60
	Min	-11807.32	-33298.55	-47042.78	-62661.62
	Mean	36386.66	16525.37	6721.52	-7943.27
Stage 2	Max	71611.73	50621.66	49331.27	45358.88
	Min	-9828.25	-31319.48	-45063.71	-59086.41
	Mean	39177.70	19316.42	9512.56	-5152.22
Stage 3	Max	86490.13	65208.36	60196.87	54106.58
	Min	966.45	-20524.78	-34269.01	-47138.17
	Mean	51473.47	31612.18	21808.32	7143.54
Stage 4	Max	91699.43	70417.65	63566.16	57235.70
	Min	4024.16	-17467.07	-31211.30	-44080.46
	Mean	55785.71	35924.42	26120.56	11455.78

The results in Table 5:9 represent the energy balance within the heat storage vessel, arraying the maximum, minimum and average values for the defined energy network combinations; positive values represent excess heat energy added to the storage vessel with negative values representing heat energy removed from storage to meet demand.

As can be seen in Table 5:9, the results show that the combination of Phase 4 with Stages 1&2, as highlighted in red, are unsustainable due to their negative average energy demand. The combinations for all Phases beyond Phase 4 were found to be unsustainable over all Stages for the same reason, as can be seen in Appendix 27. Table 5:9 also shows that in Phase 1 for Stages 3&4, as highlighted in yellow, the heat storage vessel is surplus to requirements do to the positive minimum value for both of these combinations. The exceptionally high average value combined with the positive minimum value for these combinations indicates that their implementation could result in high waste heat losses and so low system efficiency; the combinations are still viable network options although due to the low efficiency suggested by the results in Table 5:9, they are unlikely to be the best-matched network option.

The values in Table 5:9 highlighted in green represent the energy network combinations made viable with the application of heat load shifting through the use of heat storage. When considered alongside the results of the load-demand matching analysis, as shown in sections 5.1 and 5.2 above, the first thing that can be identified is the broader spectrum of network variations that become viable through the implementation of the heat storage vessel. In total, 14 network combinations in Table 5:9 are shown to have the potential to consistently and concurrently meet both the electrical and heat energy demands of the network as defined by the individual Stage and Phase of expansion. Of these combinations, two can be disregarded as having a low thermal efficiency, as stated above, which leaves 12 potentially viable network combinations.

To assist in the analysis of these results, all 14 viable network options are illustrated graphically in Figures 5:17, 5:18, 5:19, 5:20 and 5:21 below. Figures 5:17 to 5:20 illustrate the energy balance in the storage vessel for Stages 1, 2, 3 & 4 respectfully. The network combinations of Phase 1 with Stages 3&4 are shown in Figure 5:21 to demonstrate the difference between these results with high waste heat potential and the more viable results defined by their negative minimum values.

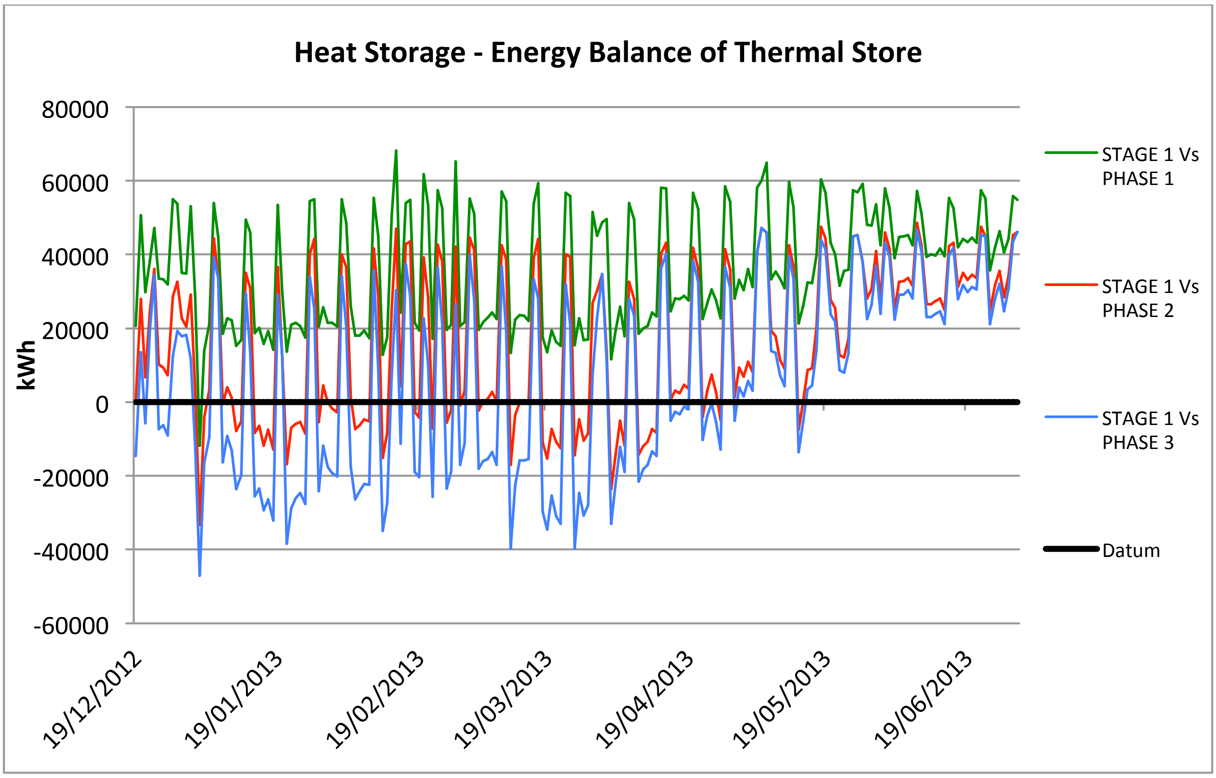

Figure 5:17 - Energy Balance of Heat Storage Vessel: Network Stage 1

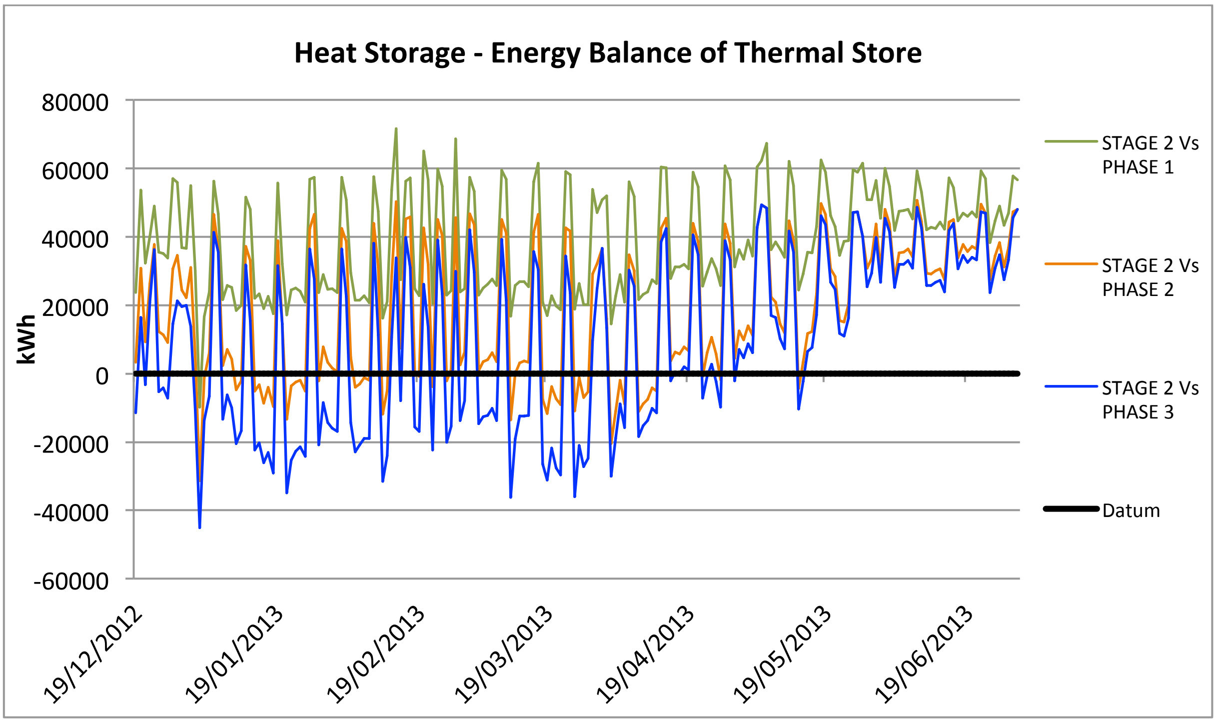

Figure 5:18 - Energy Balance of Heat Storage Vessel: Network Stage 2

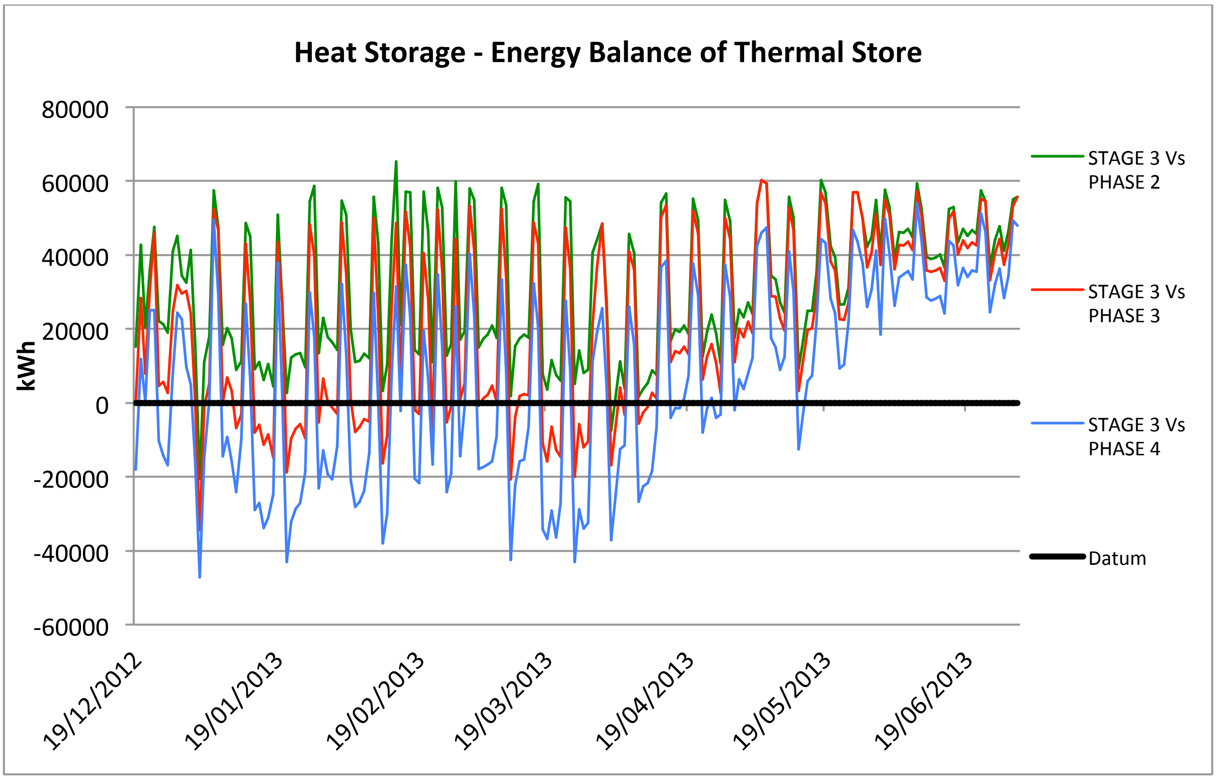

Figure 5:19 - Energy Balance of Heat Storage Vessel: Network Stage 3

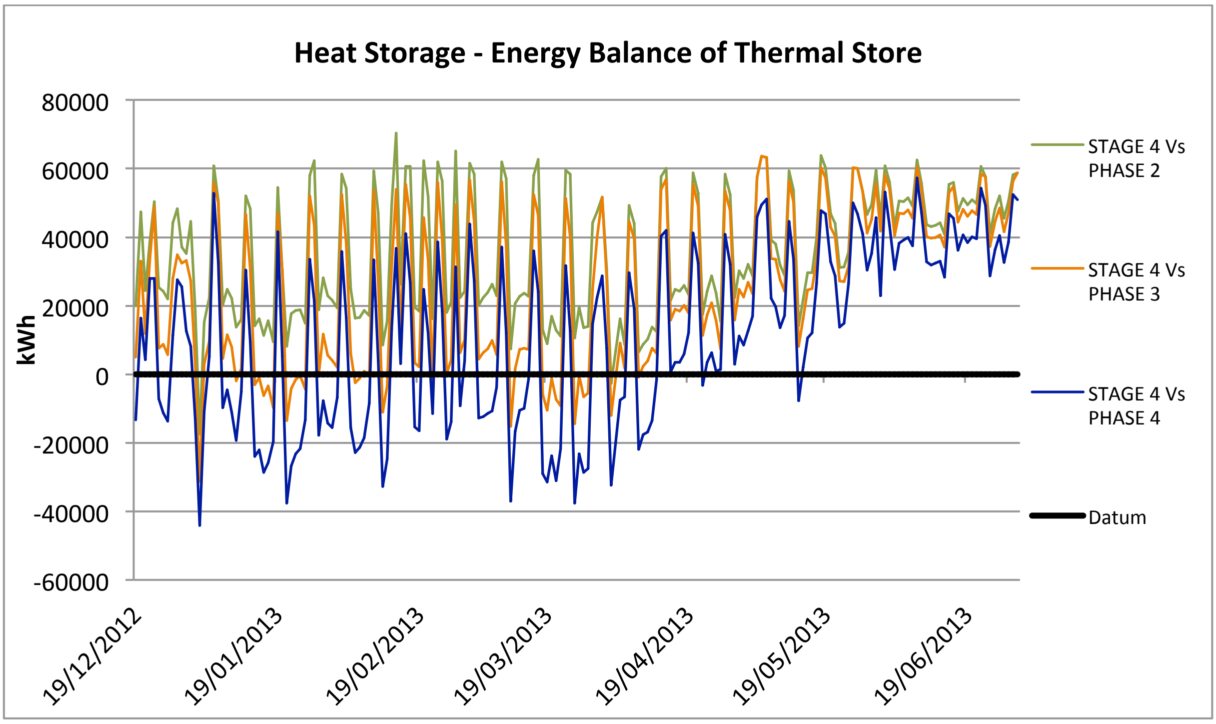

Figure 5:20 - Energy Balance of Heat Storage Vessel: Network Stage 4

Each of Figures 5:17 to 5:20 above clearly illustrate the necessary use of stored heat months to meet the demand throughout the winter months of December, January, March and into April; while the demand is more evenly matched by the heat available from the system through May and June, with much less demand for stored heat.

Figures 5:17 to 5:20 show that, even though the minimum value for the combinations of Phase 1 with Stages 1&2 and Phase 2 with Stages 3&4 is shown to be negative in Table 5:9, this occurs on essentially one peak for each system and these network combinations require very little additional energy and as such have little use for the thermal storage vessel throughout the rest of the year; this is supported by the high average value shown for these combinations in Table 5:9 and indicates that much of the waste heat could be surplus to requirement; a more expansive system Phase could therefore have a potential better match for these Stages. This is also applicable to the network combinations of Phase 1 with Stages 3&4, shown in Figure: 5:21 below.

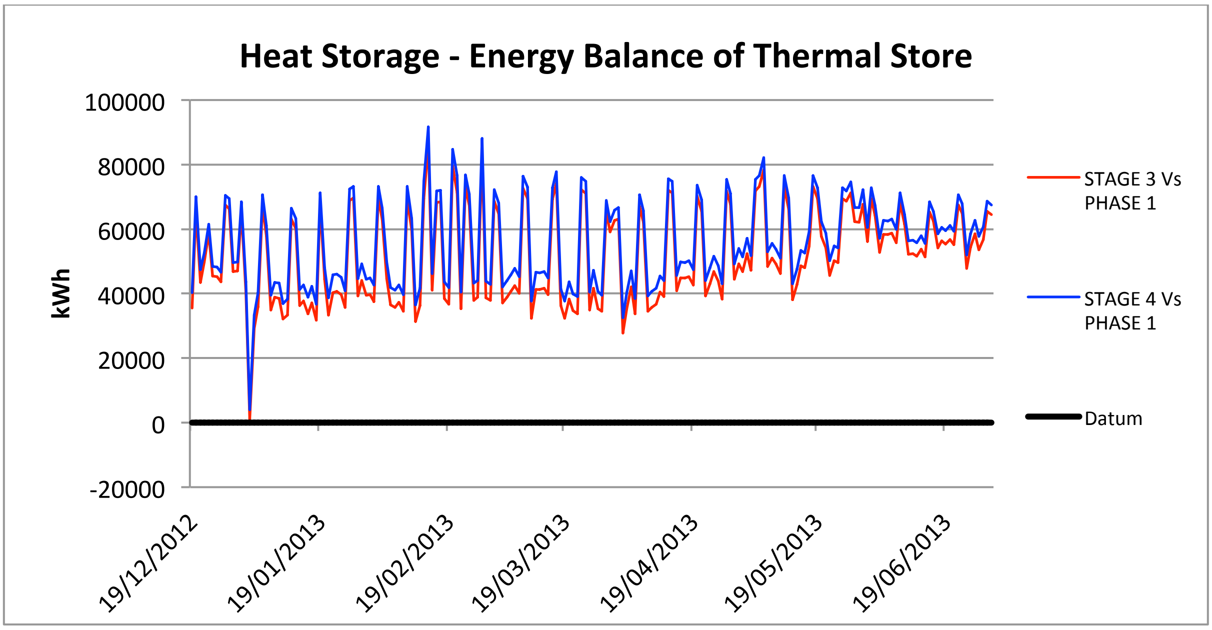

Figure 5:21 - Energy Balance of Heat Storage Vessel: Phase 1 v Stages 3&4

The results in Figure 5:21 clearly illustrate that the heat storage vessel is surplus to requirement for the network combinations shown. The high average and maximum values shown in Table 5:9 and confirmed in Figure 5:21 indicate that energy is available for these systems in the form of waste heat; however, without appropriate demand for this energy it is essentially wasted, reducing the overall system efficiency for these network variations.

Each of the other viable systems shown in Table 5:9 and Figures 5:17 and 5:18 have the potential to consistently meet the energy demands of the respective system. As each combination has this potential, selecting the best-matched system between these variations is mostly dependent on other decisions made outwith the scope of this analysis such as the scale of the storage vessel and the system cost effectiveness.

However, based purely on the results of this analysis and negating any external factors, the results shown in Table 5:9 for the combinations of Phase 3 with Stages 1&2 and Phase 4 with Stages 3&4 all have a low ratio of magnitude for the maximum and minimum values. This low ratio indicates that the maximum heat available in these systems is close to the maximum heat demand and so the system may at some points have a high reliance on stored heat; this is confirmed both by the low average shown in Table 5:9 and the graphical representations of these systems shown in Figures 5:19 and 5:20. By comparison, the results in Table 5:9 for the combinations of Phase 2 with Stages 1&2 and Phase 3 with Stages 3&4 all show a moderately higher ratio for the magnitude of the maximum to minimum values. The maximum heat stored for each of these systems is higher than for the previous four, the maximum heat demanded from storage is lower and the average heat stored is also higher; this indicates that, while there may be more heat wasted in these systems and so a relatively lower thermal efficiency, the dependence on heat stored is lower through the analysis for these systems and so the system is more reliable.

Of these four best-matched energy network combinations, the most appropriate would be Stage 4 combined with Phase 3. This network variation has the least heat demand required from storage of the four best matched options, combined with both the highest maximum and average heat input; this makes the combination of Stage 4 with Phase 3 not only the most expansive of all the best matched variations but also potentially the most reliable.

5.3.2 Use of Waste Heat for Cooling

The results of the analysis into the potential for waste heat to be used for cooling for each network combination and arrayed to illustrate the impact on the HPR using a daily time step, are shown below in Table 5:11. The calculated EPC loads used for the analysis and the complete HPR results table can be found in Appendix 28 and 29 respectfully.

Table 5:11 – Best Matched HPR Results with Cooling

	Best Matched HH HPR		
Electrical Stage:	1 - (Central)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
Max	1.1313	2.3041	3.4976
Min	0.1539	0.3157	0.4886
Mean	0.5290	1.0913	1.6576
Electrical Stage:	2 - (C & Sports Centre)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
Max	1.0961	2.3041	3.3867
Min	0.1492	0.3157	0.4734
Mean	0.5125	1.0913	1.6053
Electrical Stage:	3 - (C, SC & Graham Hills)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
Max	**0.9432**	**1.9168**	2.9060
Min	**0.1289**	**0.2642**	0.4085
Mean	**0.4526**	**0.9318**	1.4145
Electrical Stage:	4 - (C, SC, GH & TIC Building)		
Network Phase:	PHASE 1	PHASE 1 & 2	PHASE 1 - 3
Max	**0.9058**	**1.8399**	2.7887
Min	**0.1238**	**0.2537**	0.3922
Mean	**0.4341**	**0.8935**	1.3562

Table 5:11 shows the summarised results of the HPR analysis, with the best matched value for each Stage highlighted in yellow and the overall best-matched network combinations highlighted in green. These results show that the use of waste heat for cooling, with the inclusion of the additional heat demand and removal of the equivalent

heat available through the reduced electrical demand, is not a particularly viable option for the energy network.

The four best-matched network variations, according to the HPR results shown above in Table 5:11, are seen to be Stages 3&4 of the electrical expansion in combination with Phases 1&2; only the network combinations limited to Phase 1 are shown to have viable maximum HPRs. Up to this point the results appear similar to those achieved through the initial daily analysis in section 5.1.2 above, which were significantly improved through the implementation of thermal storage for peak heat load shifting in section 5.3.1; however, from the inclusion of Phase 2 onwards the maximum HPR values in Table 5:11 are shown to increase drastically to almost 100% more than achievable through the available heat. The inclusion of Stages 3&4 with Phase 2 in the best-matched results is justified by high average HPR shown for these combinations along with a relatively low maximum HPR when compared to the results displayed for the further phases, combined with the possibility of achieving a sustainable system through the further implementation of peak heat demand load shifting.

Table 5:12 below shows the results of the including waste heat used for cooling in the heat demand shifting analysis. The full table of results for this analysis can be seen in Appendix 30, with a complete graphical representation of the availability of heat in each variation shown in Appendix 31.

Table 5:12 – Summary of Available Waste Heat with Cooling

		Summary of Phased Available Heat (kWh)			
		Phase 1	Phase 1-2	Phase 1-3	Phase 1-4
Stage 1	Max	66837.16	43056.55	30134.54	19099.92
	Min	-13745.92	-91715.60	-193739.15	-295840.56
	Mean	32601.06	-24399.78	-80963.76	-137742.00
Stage 2	Max	70208.81	43056.55	32104.88	21070.26
	Min	-11766.85	-91715.60	-190213.47	-292314.89
	Mean	35392.11	-24399.78	-78172.72	-134950.96
Stage 3	Max	85087.21	56578.71	42497.78	31463.16
	Min	-972.15	-78017.99	-174783.57	-276884.99
	Mean	47687.87	-9312.97	-65876.96	-122655.20
Stage 4	Max	90296.51	60346.81	45542.00	34507.39
	Min	2085.56	-74960.28	-169336.33	-271437.75
	Mean	52000.11	-5000.73	-61564.72	-118342.96

The results in Table 5:12 represent the energy balance within the heat storage vessel, arraying the maximum, minimum and average values for the defined energy network combinations. As in the original heat storage analysis above, positive values represent excess heat energy added to the storage vessel with negative values representing heat energy removed from storage to meet demand.

As can be seen in Table 5:12, the results show that the combination Phases 2 to 4 with all Stages of expansion, as highlighted in red, are unsustainable due to their negative average energy demand. This signifies that all network Phases beyond Phase 2 have been found to be unsustainable over all possible Stages of the network expansion and that therefore only Phase 1 of the district-heating network is viable if waste heat is to be used for cooling.

The four feasible network combinations remaining can be seen illustrated below in Figure 5:22.

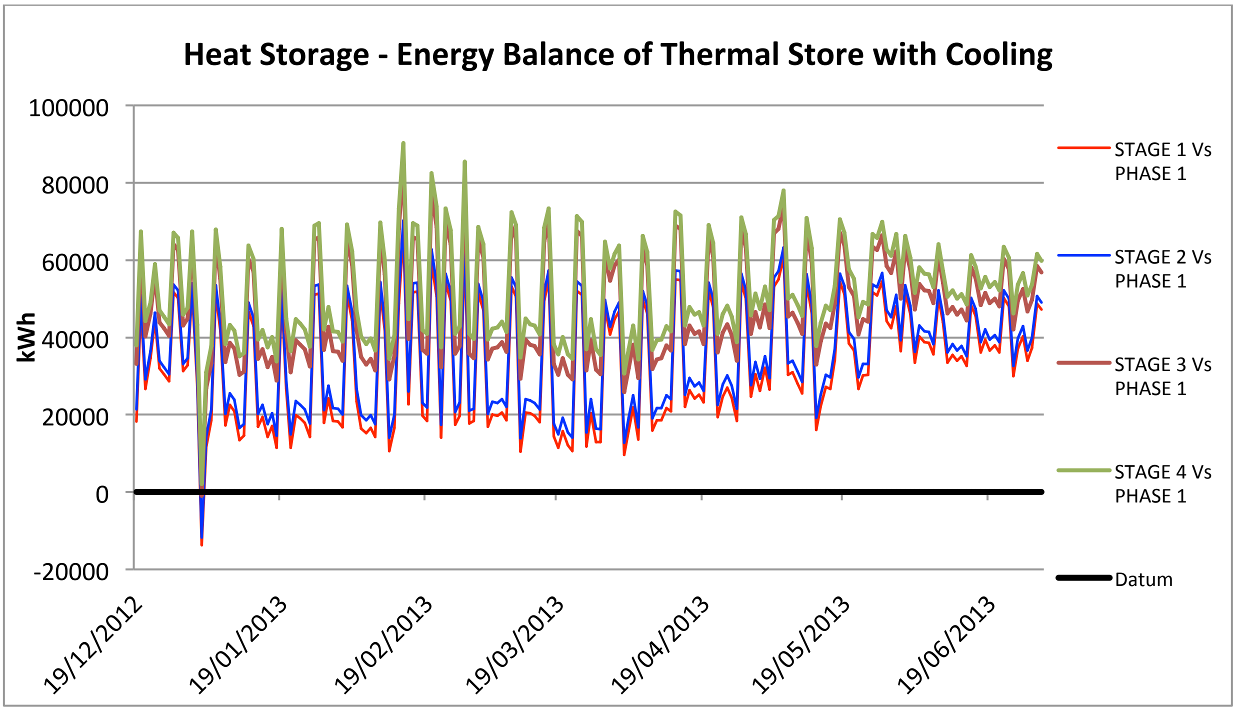

Figure 5:22 – Energy Balance of Thermal Store when Cooling is Included

The results show that for the combination of Stage 4 with Phase 1, as highlighted in yellow in Table 5:12, the heat storage vessel is surplus to requirements. This is most likely due to the large amount of heat available from Stage 4 to meet the relatively low demand of Phase 1; although Figure 5:22 also shows that the minimum for each of the other viable Phases, while still negative, is only below the datum for one occasion, on the 2nd of January 2013. Of these viable network variations, the best matched is shown to be Stage 1 with Phase 1 due to its relatively well-balanced minimum values in combination with its appropriate mean HPR value and profile. While the more expansive combinations may make use of greater levels of energy from the system, the results for these combinations indicate that this will be achieved with higher levels of waste heat than for Stage 1 with Phase 1, an indication of a more inefficient system operation.

5.3.3 Results Summary

This section sets out the results of the analysis in the preceding sections (5.1, 5.2 and 5.3) in Table 5:13 below.

Table 5:13 - Final Results Summary

	Best Matched Network Combination						
Time step	Monthly	Daily[13]	Half-hourly[14]	Monthly (AV)	Daily (AV)	Heat Storage	Cooling
Stage	4	3	4	4	3	4	1
Phase	2	1	1	4	1	3	1

Table 5:13 above summarises the results of each stage of the analysis undertaken as part of this thesis. The overall pattern formed is show to be that the larger stages of electrical expansion are aligned in combination with the lesser degrees of heat network expansion; the exception to this pattern is the final cooling analysis, which indicates a generally poor match for the use of waste heat to meet the cooling demands on the campus.

[13] This Daily combination is the best possible match according to the analysis when there is no peak heat load shifting available through heat storage.
[14] As no half-hourly result was viable in the analysis, this selection represents the nearest viable network combination as it has the lowest maximum HPR value as shown in Table 5:4 above.

Of the other analyses completed in the course of this assessment, the most appropriate result appears to be that taken from the heat storage analysis of Stage 4 with Phase 3; this result is not only in general agreement with the more static analysis carried out in the earlier stages of the process, but the analysis from which this result was achieved has also been shown to be the most accurate representation of the anticipated operation for the proposed energy network. This accurate system representation, combined with the result validation against those from earlier forms of the demand matching analysis, allows the final result from this analysis to be that the overall best-matched energy network combination is for Stage 4 of the electrical network expansion, representing the full generating capacity of the campus, to be combined with Phase 3 of the district heating network which is representative of the Island Zone, Business Zone and Sports Centre.

6 Discussion

This section of the report aims to critically examine the findings shown in the results and analysis section (5) above in comparison to what was already known about the proposed campus energy network, judging what has been learnt as a result of this work.

The primary result achieved through the analysis was the assessment of the proposed district energy network to a degree of accuracy that has up to this point not been available. The viability of the system has been assessed through the demand load matching of various proposed network combinations down to half-hourly time steps and has shown several of these combinations to be feasible, particularly through the implementation of peak heat load shifting using thermal storage and with a more limited viability found for the use of potential waste heat for cooling.

One potentially limiting factor for the analysis in general is that the use of heat from the system is not instantaneous in reality; the demand may occur concurrently however the process includes the generation heat in a unit some distance from the demand then transporting the heat across that distance. This can clearly result in some degree of lag that has not been considered for all analytical stages of this project; however the effect is partially anticipated in the heat demand matching section of the analysis through assessment of overall energy balance rather than immediate demand.

With regard to the results achieved, one unanticipated finding was that analysis based purely upon half-hourly demand matching could only conclude that the system is not viable for any possible network combination; but significantly this conclusion was effectively negated through the implementation of heat load shifting in the next stage of the analysis. The highlights the risks involved in basing any decisions made regarding the system on the conclusions of only one results set. The results of the monthly demand matching analysis offer only a very generalised view of the interactions between the demand profiles, the same can be said to a lesser degree for the daily analysis while the half-hourly analysis shows the demand almost exactly as it occurs. That said, this last representation is bordering on being too accurate for the purposes of a demand matching analysis as it is highly unlikely that peak electrical and heat loads will occur exactly within half an hour of each other, with the resulting conclusions therefore inevitably matching those stated above. By simulating the potential for heat storage in the system it effectually takes the edge off of this excessively accurate representation of the interactions between the demand profiles; more appropriately representing the interaction between the heat generated by the system which has to be effectively stored in the fluid of the district heating network before it can be used. Demand matching and HPR analysis is therefore shown to be a good basis for the sizing and design of a potential district energy network, however dynamic analysis of the system is clearly the only way to accurately represent the incredibly complex interactions between each of the demand profiles involved. As stated in the analysis and results section above, it is for these reasons that the energy network analysis can be considered the most accurate representation of the actual energy network included in this report.

Regarding the validity of the results and quality of the conclusions achieved in this analysis, the key issue to be considered is that the energy analysis has been based entirely on the assumption that gas demand represents heat. By assuming that gas equals heat the analysis process becomes much more straightforward due to an ignorance of generation efficiencies and losses within the current heating system; however, this also makes the analysis more inaccurate for those very same reasons. Aside for the simplicity of analysis however, the main advantage of assuming gas as heat is that the system being analysed is being assessed against a higher heat demand than is actually required and therefore the assumption can only result in the generation of excess rather than lack of available heat. By falsely representing the heat demand as a higher value than it actually is the true impact of this assumption on the results is therefore a potential reduction in thermal efficiency of the system, but only if it were to be designed directly from the conclusions stated here.

One possible limitation of this assumption on the conclusions made from this analysis is that, by effectively assuming a higher heat demand than is actually present, the final Phase of district heating network expansion selected may be lower than the system is actually capable of meeting. For example, Phase 3 has been selected as the most appropriate Phase of energy network expansion according to the results of this analysis; however, due to the artificially high heat demand through the analysis, the system may in fact be able to effectively achieve up to Phase 4 of the network expansion when the actual system efficiency is implemented.

The original decision to make this assumption was based upon the fact that any potential efficiency applied would have been entirely based upon alternative assumptions such as generalised boiler efficiencies and the proportions of heat met in the system by alternative boiler combinations; assumptions that could have resulted in an equal if not greater impact on the results. The falsely high heat demand in the analysis also makes the results less vulnerable to any unanticipated losses from the heat network. It can therefore be concluded that, while more exact demand figures should be used when sizing the system for design and implementation, for the purposes of this analysis the assumption that gas equals heat is valid and has not negatively impacted the analytical conclusions.

Another assumption that could have potentially significant impact on the analysis is taking the CHP generation efficiency to be 1:1 for heat to electricity. The effect this could have on the results cannot be understated, as even a small change on either side would greatly impact the profiles and HPR generated throughout this analysis. However, not only was this assumption based on analysis carried out in previously commissioned reports[15], but the use of a 1:1 ratio makes the results achieved here easily interchangeable into any future analysis. The reality of the campus energy project as it stands is that no final design decisions have yet been made and therefore to make use of a very specific CHP ratio would limit the validity of the results of this analysis much further than assuming the ratio as 1:1.

The next major factor, which could potentially limit the application of any conclusions achieved in this report, is that the entire analysis has been built around what are essentially hypothetical building combinations and energy network variations. The implementation of these area-based assumptions on the analysis limits the results to the network combinations included in the assessment. For example, the analysis is based entirely on the inclusion of the island zone; represented as Phase 1 of the potential heat

[15] (Palmer & Tamburrini, 2007)

network and no network arrangements were analysed to the exclusion of this Phase. However, while the implementation of the area based Phases of expansion may at first seem to limit the application of the analysis, each assumed Phase of expansion was carefully based around the likely anticipated expansion of the energy network as outlined in the project proposal[16]. This expansion is based upon the island zone as this represents the greatest localised energy demand on the campus, as illustrated in the analysis above, expanding first along Cathedral Street from this point, initially avoiding any potential complications that can arise in attempting to install such a system on steep hilly locations[17], before then progressing to include steadily more potential sites downhill on the campus. With regard to the Stages of electrical expansion, very little was in fact assumed; once it was made clear that the basis for the electrical demand would almost undoubtedly be the Central Substation the inclusion of the further Stages simply extended to include the available demand. Overall there can be no doubt that the assumption of network variations in this analysis has limited the application of the results, although this limitation is essentially due to the time limits placed upon the analysis and as such kept the analysis firmly within the scope of the project.

The use of profiled data to represent both the Sports Centre and the Technology and Innovation Centre is another factor that could potentially call the results into question. With all the other data sets that were used taken from metered data there is a possibility that the use of generated data could undermine the quality of the assessment. The key factor regarding the use of profiled data to represent these two buildings is that they do not currently exist and so no metered data is available. Without running a full building simulation of the proposed structures, a task that could possibly be worthwhile but undoubtedly beyond the scope of this project, the only energy consumption data available other than from CIBSE guides is that provided in the EPC certificates; with the only viable method of including this data in the analysis being the application of this anticipated consumption over a profile. As stated in the justification of this assumption in Appendix 4, the use of profiled data is the trade-off for including these constructions in the analysis and due to their anticipated prominence in the future campus model their inclusion was considered vital.

[16] (Estates Dept. University of Strathclyde, 2012)
[17] (Harvey, 2006)

The generation of the percentage profiles from existing structures on the campus could be considered to be a perceivable flaw in the methodology for the inclusion of this data. Using the profile of the Sir William Duncan to represent the TIC Building was a reasonable assumption considering their similar anticipated usage patterns, however the use of the Curran Building to represent the Sports Centre is not likely to be a true representation of the Sports Centre's energy use. This decision was made as of a profile for a Sports Centre building type was not present in the data provided and the Curran Building, with its constant use and high heat demand, was the best matched of those available. The use of profiled data is not ideal but in any live plan with proposed projects constantly evolving and moving forwards, it has its place. In the case, with the use of the Curran building profile, the assumptions made are still justified and their impact on the analysis has been limited. At this time, the only way to include the Sports Centre and TIC building in the analysis was through the application of purely representative data; taken either from simulation, which was outwith the scope of the project, or the use of percentage profiling. This was achieved accordingly, with the only method of improving the analysis being to create a more accurate representative data set. The analysis and resulting conclusions were therefore as accurate as was possible while remaining within the scope of this project. The positive impact of including these currently hypothetical structures in the campus energy analysis completely outweighs level of possible inaccuracy from their representation; especially as the demand profiles are based upon the roughly anticipated energy demands of the buildings in question.

The total effect on the conclusions resulting from the inclusion of these profiles was actually shown to be relatively small when compared to the other Stages and Phases of expansion. For each time step the inclusion of the electrical demand profiles of the Sports Centre and TIC Building, in Stages 2 and 4 respectively, typically increased the viability of the best matched Phase from the previous Stage through the increased availability of heat. One of the few exceptions to this trend was in the Daily analysis, both for the original and averaged data sets, where the best-matched combination was shown to require Stage 3 of the electrical expansion. Only the inclusion of the heat demand from the Sports Centre has any impact on the conclusions as after very few results sets showed any network Phases beyond Phase 3 to be viable. Without the inclusion of the Sports Centre heat demand it is likely that the Phase 4 or even Phase 5 of the network expansion would have been concluded as the best-matched network combination through the Heat Storage analysis; although this result essentially validated the inclusion of the Sports Centre in the analysis as expansion up to its inclusion was shown to be the most valid network structure in what could be considered the most accurate energy network assessment undertaken in this project.

A similar factor in the analysis that could call the results into question is the creation and application of the cooling profile. This was undertaken not only through simulation in Esp-r, but also based upon the temperature profile rather than a cooling load from the model. However, for much the same reasons as the use of profiled data was justified to include the Sports Centre and TIC Building, as there was no applicable cooling data available for use in the analysis any profiles used would again be purely representative. Any question over the quality of the cooling profile is therefore essentially irrelevant as the profile applied represents the cooling data of the campus as accurately as is possible without data that not only is outwith the scope of this project but could only be gathered by vastly increasing both the workload and time required to do so; the practicality of which would have to be carefully balanced against the anticipated benefit.

The inclusion of absorption cooling in the network was also a purely hypothetical aspect of this analysis; carried out to identify the potential viability of this technology in the reduction of waste heat, which would thereby increase the efficiency of the system. The impact of the assumed profile would therefore be negligible to the overall conclusions for the analysis and, even with regard to the cooling assessment itself, would not devalue the results obtained.

The last of the assumptions that could feasibly affect the robustness of the conclusions stated here is the decision taken to ignore system losses in the energy network. While this assumption, much like the assumptions of gas as heat and the 1:1 HPR of the CHP, vastly simplified the analytical procedure and allowed greater scope for the project; it could also have a negative impact on the validation of the results. However, ignoring the losses from the district heating network was a decision made not only to simplify the analytical process but also due to the unknown quantity that the network itself represented; the investigation of which was originally for this project but deemed to be outwith the scope of the chosen analysis due to its complexity and the high degree of assumptions required. The assumption to ignore the network losses thereby ensured more robust conclusions than the generation of these losses from a completely hypothetical network construction. The analysis was also undertaken primarily to build a pattern of demand and consumption to assist decision makers, while concurrently promoting a more informed analysis of more complex design issues in the future; the conclusions achieved have successfully done so and their quality is not greatly reduced through the non-inclusion of the network losses in the analysis. The analysis and calculations shown here could easily be repeated with the inclusion of the losses when available and the conclusions drawn would be proportionately similar due to the high degree of accuracy achieved in the comparison of the systems involved.

Aside from the assumptions made, there are also potential data quality and processing factors included in this analysis that also could affect the conclusions achieved. For example, the limitation of the half-hourly gas data set to only six and a half months of appropriate data presents a possible issue with the quality of the analysis. By only assessing the loads across a portion of the year an essentially incomplete profile is created, which inevitably also results in an incomplete analysis. The analysis was based upon the available data and as such could not be improved; the question is therefore whether this incomplete result set has negatively impacted the quality of the results and the conclusions drawn or that the overall effect has been negligible and the conclusions are robust.

The absence of July and August from the analysis could potentially skew the results of the HPR generated for any system assessed towards an artificially increased efficiency as these months typically represent the lowest demand for heat. However, as the months of September, October, November and the start of December are also missing from the analysis, the impact has effectively been minimised through the typically higher levels of heat demand of these months, which would generate an opposite effect on the HPR. Considering that the half-hourly data set extends from December through to June, essentially encompassing the energy demand profile of the entire campus from Winter to Summer, it is possible to conclude that while a more complete half-hourly analysis would undoubtedly have been preferable the conclusions reached regarding the system viability through the available data set are robust enough for the purposes of recommendation; as was the primary goal of the project.

One final factor regarding the quality of the analytical process is the use of Microsoft Excel for the simulation and calculation aspects of the analysis. Excel is a very powerful analytical tool when used in the appropriate manner, although the spreadsheet format tends to rely on fairly static analysis whereas more specialised programs, such as MERIT, exist purely for the purpose of dynamic simulation of supply and demand matching. In the analysis carried out above, the profiling and comparison of demand variation and HPR over time represented a more traditional form of spreadsheet based dynamic analysis, while the investigation into the application of heat storage and heat for cooling considered the variation and interaction of more factors within the analysis over time and could be considered a more dynamic use of Excel. The use of a specialised program could possibly have produced more accurate analytical results; however, this could also have limited the overall scope of project through the additional time constraints potentially generated through the necessary conversion and input of data from Excel to the program, combined with the time required to become adequately proficient in the use of this additional program.

While this analysis was able to assess a variety of different factors that could affect the final design of the energy network, the application of a specialised program to analyse a proposal to the scale of the energy network assessed here could potentially have represented a completely separate thesis topic in itself. The use of excel therefore allowed the analysis to focus on the investigation of the data sets, achieving the desired results in a manner that is repeatable. The use of Excel cannot be said to limit the accuracy of the results as the analysis is primarily based upon a data comparison for which the program is entirely suited, with the quality of the results more dependent on the data quality as has been discussed above. The more specialised analyses undertaken may have been more restricted than could have been possible through the use of software specifically designed for that analytical purpose, although the demands required in application of such software was outwith original the scope and work plan of this project. The results of the Excel analysis were also more than adequate to achieve the desired level of recommendation and conclusions stated at the project outset.

Overall the analysis undertaken has achieved the original goals of project and defined a set of results that clearly outline the potential interactions of the proposed energy network, which have in turn led to conclusions regarding the network viability. Considering the analysis from all angles, as set out in the discussion above, it can be also said that the conclusions achieved regarding the viability proposed energy network are both robust and applicable to the proposed network as it currently is currently envisaged.

7 Conclusions

This section aims to summarise the findings of this thesis, define the final conclusion from the work and demonstrate the achievement of the goals set at the start of the study; also included are the recommendations for both further practice and further work.

7.1 Final Results Summary

The primary result achieved in this study is that, according to analysis of half-hourly metered demand data for the entire John Anderson campus, the most appropriate network variation for the potential district energy network is for Stage 4 of the electrical network expansion in combination with Phase 3 of the district-heating network and waste heat storage.

This combination of Stage 4 and Phase 3 represents the electrical demand for the entire John Anderson campus combined with the means to store and redistribute waste heat and a district heating network that meets the heat demand of the Island Zone, the Business Zone and the Sports Centre.

Through analysis of data from the monthly, daily and half-hourly time steps it also became clear that for load demand matching the application of daily data – calculated using the half-hourly data set - provided the most appropriate results; this was a balance between the monthly data, for which the results were too general to be accurate, and the half-hourly data, which profiled the demand so accurately that no possible match could be found for any combination.

The inclusion of the Sports Centre and TIC building, considering that these are only two proposed structures, were found to have fairly large impact on the analysis. This is particularly true with regard to the district heating system, where the Sports Centre was found to be the optimum final stage in the expansion of the network. The TIC building had little impact on the district heating analysis as, due to its position as the final Phase in the expansion of the system, its inclusion in the heating network was never shown to be an option. The TIC building had a more serious impact on the electrical grid however; with the inclusion of available heat generated through its inclusion making Stage 4 best matched final expansion of the network.

Waste heat storage was found to be a viable prospect for the energy network, significantly improving the viability of most network variations when compared to analysis based purely demand load matching. However cooling through the use of waste heat in absorption chillers was not found to be a feasible option unless the district heating network was limited to only the Island Zone.

These final conclusions represent the achievement of each of the aims and objectives set out at the start of this project, as summarised below:

- Real, recorded demand data was used (wherever possible) to assess and compare both heat to power ratios and load demands over the proposed network for monthly, daily and half-hourly timeframes
    - The most appropriate network combination was identified
    - The advantages and disadvantages for each timeframe were illustrated
    - The impact of the TIC building and Sports Centre on the network were assessed and included in the analysis

- The quantity and possible uses for any waste heat that may be generated by the network were investigated
    - Waste heat for anticipated network combinations was quantified
    - Potential for demand load shifting was assessed
    - Use of excess heat for cooling purposes was examined

As has been previously stated, key assumptions have been made upon which this analysis has been based; two of the most important being the use of a nominal HPR value of 1:1, the justification of which can be found in Appendix 4, and the exclusion of transmission losses, as justified in section 2 above. To illustrate the sensitivity of the results, and thereby the conclusions, to these assumptions, a brief illustration of the potential impact that their alteration could have on the overall recommendations is shown in Table 7:1 below. This table shows the impact that altering the nominal HPR to 1:1.5 or 1:2, and also the inclusion of 15% transmission losses would have on the results of the Heat Demand Shifting analysis, as shown in section 5.3 above.

Table 7:1 – Potential Impact of Altered Key Assumptions

	Best Matched Network			
	HPR (1:1)	**HPR (1:1.5)**	**HPR (1:2)**	**HPR (1:1) 15% TL**
Stage	4	4	2	4
Phase	3	6	9	2

These illustrative results were achieved through re-evaluating the initial stage in the heat demand shifting analysis using the assumptions stated above. The results show that by assuming ignorance of the losses this study could have resulted a slightly more expansive recommendation than is possibly viable. This is in contrast with the increase of the assumed HPR value for the CHP unit, which expectedly allows far greater expansion of the district-heating network than is possible with the 1:1 ratio. Of particular interest is the result for the 1:2 ratio, which shows that at this rate of generation there could be enough heat available to match the full campus demand without requiring the full electrical generating capacity; this shows there could be potential for heat exportation from the campus network through the use of more expansive CHP generation.

The results in Table 7:1 show that by the application of a specified HPR ratio to this study, the modelling and analysis undertaken can be utilised to properly inform the design team of the appropriate network variation best suited to their goals.

7.2 Recommendations for Further Practice

The recommendations for further practice represent the steps advocated to potentially increase the effectiveness of any further analysis, either of this same subject or for any similar analytical process. These have evolved as a direct result of the work undertaken for this project through consideration of those aspects of the analysis that could have been expanded upon or improved to make the conclusions achieved even more robust and of yet higher value to the project stakeholders.

After completing and assessing the results of multiple analyses, both of a dynamic and static nature, it is strongly recommended that any further investigation be based upon purely dynamic analysis. The results of static energy analysis, as shown in the results defined in section 5 above, can be very misleading and potentially flawed in use for anything more advanced than the basis of a design.

It is also recommended that the data formed from the energy metering necessary to undertake an analysis of this type be standardised, or at the very least an automated system developed for the processing of such data into a form that is fit for comparison. An inordinate amount of time in this project was spent purely on data processing and validation; if this procedure was to be simplified then any further undertakings could be more focussed on the analysis itself, which in turn is likely to produce a higher quality of analysis.

Any further investigation of this kind is also recommended to take the impact of emissions into account through the analysis of the energy network. The reduction of emissions is clearly a considerable factor (HMRC, 2013) (Department of Energy and Climate Change, 2013) in increasing the viability of district heating networks in the UK and as such the inclusion and quantification of this factor in the analysis would increase the value of any conclusions drawn for the appropriate stakeholders.

It is also recommended that a financial element is included in any further analysis. Apportioning a financial figure to any calculated energy savings allows a comparison with the anticipated capital cost for each stage of expansion in the projects development. This would increase the overall value of the conclusions achieved allowing more informed decisions to be made.

With particular regard to this project however, many of these recommendations for future practice are only achievable to an acceptable degree of accuracy through access to more information than was, or could be, made available for this study. For further study to be of any more value to the project stakeholders there must be less reliance on assumption; this requires decisions to be made, advancing several stages and key factors within the project beyond "potential" and into planned design.

7.3 Recommendations for Further Work

The recommendations for further work are similar to those for further practice although these have been generated through consideration of how the project itself could be expanded and improved, rather than the analytical process itself; the recommendations for further work indicate how this thesis project could be valuably taken further and the conclusions achieved here improved through further analysis.

The first clear recommendation for furthering the work undertaken in this thesis is the inclusion of half-hourly data over a full twelve-month period. Although due to the limitations of the available data and so completely unavoidable, this was one of the most significant limiting factors within this analysis. Inclusion of half-hourly data for a full year would allow a complete picture to be created of the demand on the campus, which would in turn facilitate more accurate comparison and analysis than was possible here.

The primary recommendation for further work is the analysis of the impact of on going demand reduction throughout the campus on the energy demand that the proposed energy network is required to meet. This was originally one of the goals of this thesis project, however the scope of the project had to be restricted due to the limited time frame. If the energy network is designed to current demand of the campus and this demand is significantly reduced then the efficiency of the system is also reduced along with the viability of the energy network. The impact of the on going demand reduction across the campus is not anticipated to lower the demand to such a level that the energy network is no longer a feasible option for the campus, however the impact of such measures should definitely be assessed.

In the same manner, expanding the analysis undertaken here to include the future plans for the campus infrastructure would highlight any combinations that are potentially not viable due to anticipated changes in the building stock of the University. For example, if the Royal College Building was to be removed from this analysis is highly likely that the conclusions would be very different.

Another aspect of this analysis that could be expanded, particularly through the availability of half-hourly data for the full year as stated above, is the investigation into potential heat storage. According to the results of the monthly demand data, there is a large degree of waste heat available through the summer months, particularly July and August. It is therefore recommended that the potential to store this waste heat for use in the future be assessed; by "charging" the storage vessel in July and August, any waste heat through the Autumn could be used to maintain this stored body as a buffer for heat required through the Winter. This is obviously completely dependent on losses over time from the storage vessel but dynamic analysis of such a system would reveal or dismiss any potential for the arrangement.

Increasing the scope of the waste heat analysis carried out in this thesis to include the use of half-hourly demand data could possibly increase the accuracy of the results from that section of the study; also conceivably making the half-hourly data set more viable for future analysis as the impact of the vastly contrasting demand found here could be subdued through the peak heat demand shifting effect seen in through the application of heat storage.

The expansion of the analysis to allow partial heat load of some sites could also develop the potential for the district-heating network. The current analytical method identifies only those combinations where the entire heating load can be met; by allowing for the possibility of top up boilers on site to meet peak demand the potential for the district heating system, and as such the district energy network, could be greatly increased.

The analysis of a district-cooling scheme for the campus was considered to form part of this thesis but a more limited investigation into the general viability of absorption chillers was decided to be more appropriate. The expansion of this analysis to include a full district-cooling network could therefore be beneficial further work, particularly if combined with an accurate measurement of the on site cooling demand. This analysis would allow a definitive conclusion to be drawn as to the viability of waste heat to be used for on campus cooling although it is not likely to be the case as the preliminary results achieved from this analysis are not very promising.

Another aspect of this analysis that would be recommended for further work is the scale and overall design of the proposed district-heating network itself. It is likely that this form of analysis would be heavily based on assumptions as this stage of the project, however this reliance on assumptions will reduce as and when the project develops further. The analysis should include calculation of pipe length and diameter for each stage of the expansion to allow cost comparison as well as energy demand matching; this would also facilitate the calculation of dynamic losses and potential investigation of the possible relationship between the underground pipe networks of both district-heating and cooling schemed installed for the same site.

The final recommendation for further work is the assessment of benefits and drawbacks of the various fuel types that could potentially be used to power the energy network; from emissions impact and overall cost down to efficiency and fuels storage issues. This topic has been touched on already in some of the previously commissioned work, although a more detailed investigation is recommended once the system has been definitively sized and planned.

7.4 Final Conclusion

The analysis undertaken in this report has been, by necessity, predicated upon the assumption that finding and installing the best matched energy network combination will be the first priority in the system design. If this assumption proves to be true then the conclusions are robust. However, if they prove false, if the determined priority of the system design is not to be overall energy efficiency, then as the final system is to be judged on factors outwith the scope of this project the conclusions stated here will not apply.

This is common issue with work undertaken on prospective or proposed systems though, and in this case the results of the demand matching, HPR and heat load shifting analyses carried out are still completely valid as the results are based on real data. The more constant value of the work undertaken in this study is therefore that while the conclusions stated are dependent on the assumptions made in the application of the results, the results themselves are valid and as such could be used again to achieve an alternative set of conclusions based on an alternative set of assumptions.

The key assumptions made in this analysis are all based upon real data or data achieved through previous analysis and as such are as close to the actual system as was possible at the time; the conclusions made in this report were therefore achieved using the closest possible representation of the energy network available and shall only lose their relevancy if the energy network proposal moves on from the stated base assumptions that were the foundation of this analysis.

On the basis of the analysis done, the most viable network arrangement for the University of Strathclyde John Anderson Campus district energy network is the combination of the electrical demand of the entire campus matched with the combined heat demand of the Island zone, Business zone and the planned Sports Centre and unless the system boundaries are changed this will remain to be the case.

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9 Appendices

Appendix 1 – Data Processing: Assumed Phases of Network Development

Table 9:1 - Assumed Phases of Heating Network

Energy Network Expansion Phases	
Phase 1	Royal College Building
	James Weir Building
	Thomas Graham Building
	Students Union
Phase 2	Hamnett Wing
	Henry Dyer Building
	John Arbuthnott - Robertson Wing
	Sir William Duncan Building
	Stenhouse Building
	Strathclyde Business School
Phase 3	Sport Centre
Phase 4	Curran Building
	Lord Hope Building
	181 St James Road
Phase 5(a)	Residences (Central Substation)
Phase 5(b)	Residences (Graham Hills Substation)
Phase 6	St Pauls
	University Centre
	Lord Todd
Phase 7	Architecture Building
	Colville Building
	John Anderson Building
	Wolfson Centre
Phase 8	Collins Building
	Livingstone Tower
	McCance Building
Phase 9	Graham Hills Building
	Barony Hall
Phase 10	TIC Building

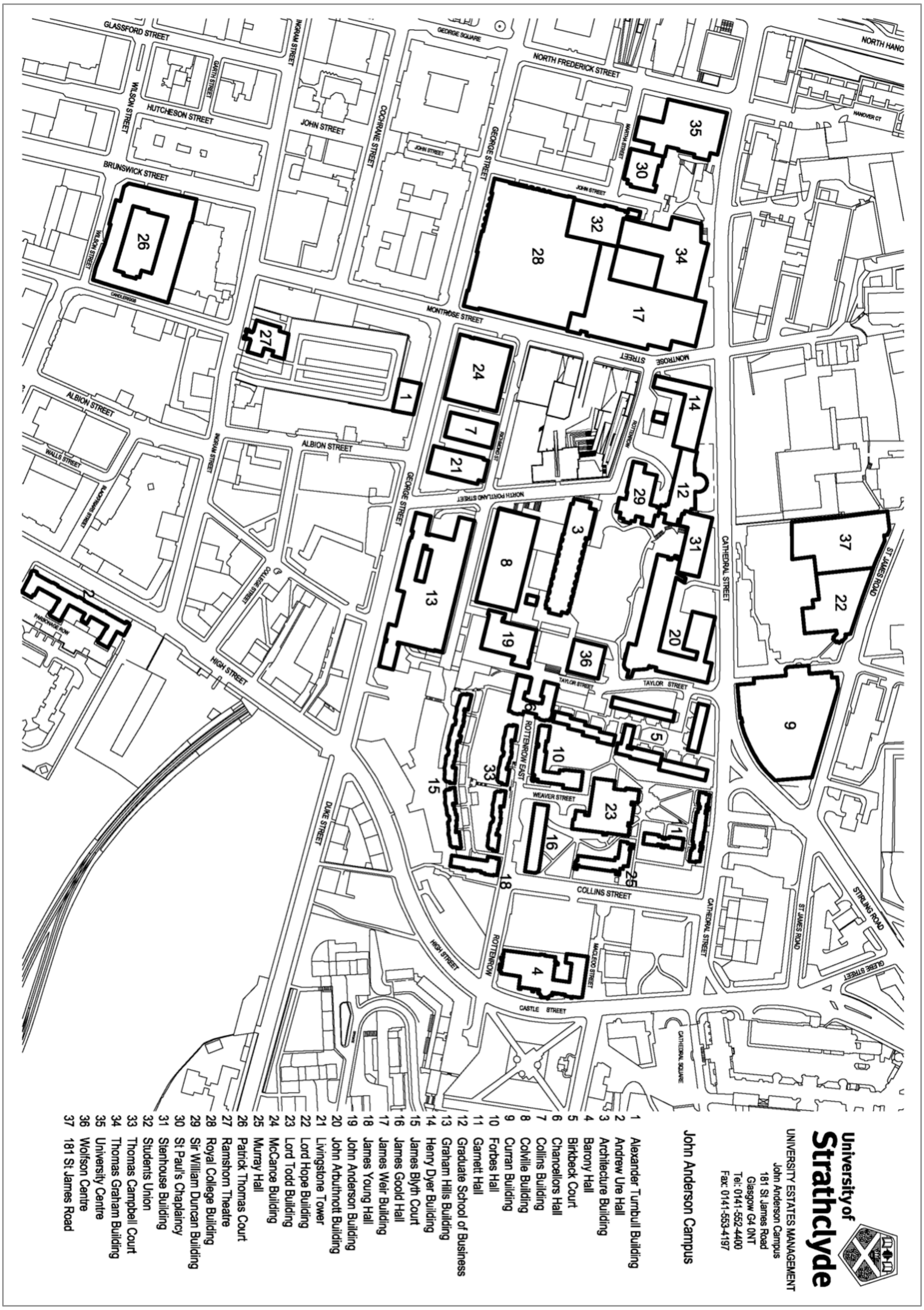


Figure 9:1 - Numbered Map of The University of Strathclyde - John Anderson Campus

Appendix 2 – Data Processing: Division of Campus by Electrical Substation

The division of the buildings between the Central and Graham Hills substation, as taken from the campus power network diagrams and according to their relevant project phase can be seen below in Table 9:2.

Table 9:2 - Division of Campus According to Substation

Development Phase	Building	Substation
1	Royal College	Central
	James Weir	
	Thomas Graham	
	Students Union	
2	Hamnett Wing	Central
	Henry Dyer	
	J.A (Robertson)	
	Sir William Duncan	
	Stenhouse	
	S.B.S	
3	Sport Centre*	Unknown
4	Curran Building	Central
	Lord Hope Building	
	Estates Services	
5	Birkbeck Hall	Central
	Chancellors Hall	
	Forbes Hall	
	Garnett Hall	
5	James Blythe Hall	Graham Hills
	James Goold Hall	
	James Young Hall	
	Murray Hall	
	Thomas Campbell Court	
6	St Pauls	Central
	University Centre	
	Lord Todd	
7	Architecture Building	Central
	Colville Building	
	John Anderson	
	Wolfson Centre	
8	Collins Building	Central
	Livingstone Tower	
	McCance Building	
9	Graham Hills	Graham Hills
	Barony Hall	
10	TIC Building*	Unknown

Appendix 3 – Data Processing: Full Results of Electrical Data Validation

Table 9:3 below illustrates the percentage difference of the monthly electrical data set that is met by the totalled electrical half-hourly data set. For example, in May 2011 the total half-hourly data demand is 14% greater than the demand manually recorded for that month.

Table 9:3 - Full Electrical Data Set Validation

	Monthly Reading		**Monthly (HH) Reading**		**% Matching**	
	Central Total	GH Total	Central Total	GH Total	Central	GH
MAY 2011	2148318	321989	2453390	334738	114%	104%
JUN 2011	1983514	292860	2139874	285284	108%	97%
JUL 2011	2039687	276810	2063650	269839	101%	97%
AUG 2011	1981992	283349	2169048	277329	109%	98%
SEP 2011	2054081	313245	2145787	293404	104%	94%
OCT 2011	2327521	360560	2453474	386339	105%	107%
NOV 2011	2509313	384112	2487225	396769	99%	103%
DEC 2011	2602640	405917	2422905	390659	93%	96%
JAN 2012	2445481	338591	2581810	403826	106%	119%
FEB 2012	2499079	362852	2480759	394800	99%	109%
MAR 2012	2670855	386219	2544842	382010	95%	99%
APR 2012	2396818	336763	2375595	346227	99%	103%
MAY 2012	2561965	315900	2446034	348345	95%	110%
JUN 2012	2267193	273871	2134869	274152	94%	100%
JUL 2012	2187932	267289	2267723	282593	104%	106%
AUG 2012	2298474	282609	2340808	264000	102%	93%
SEP 2012	2208881	278862	2277408	289323	103%	104%
OCT 2012	2548063	371159	2596311	372949	102%	100%
NOV 2012	2755480	404984	2653320	393543	96%	97%
DEC 2012	2395365	375614	2520692	376639	105%	100%
JAN 2013	2623284	394690	2774682	406675	106%	103%
FEB 2013	2580224	386796	2620549	375029	102%	97%
MAR 2013	2450340	389761	2844821	417938	116%	107%
APR 2013	2292760	355321	2655434	361237	116%	102%
MAY 2013	2341206	423811	2596922	360138	111%	85%
JUN 2013	2013328	194721	2350337	279777	117%	144%

Appendix 4 – Methodology: Justification of Assumptions

- Processing of Half-hourly and Monthly data sets

The impact of the final building meter coming online (John Arbuthnott Robertson wing on 01/04/13) can be seen in Table 3:3 through the percentage increase in Phase 2 for those months that it is included; the decision was therefore taken to profile the demand of this building back to the 19th of December. This would use the Monthly demand for these months applied to a percentage profile taken from the John Arbuthnott Hamnett Wing, assumed to be its closest equivalent.

Most other instances of missing or erroneous data were largely found to be innocuous. Taking the demand for the same time period in the previous week and copying this in for the missing data resolved instances where data entries were missing for short periods. The large portion of erroneous data identified for the John Anderson building (MPR – 14468605) and the data spike also identified in this profile were assumed to be accurate; while the readings may be unusual, the values were consistently recorded at each time step and such were assumed to be part of the energy demand profile.

The decision to limit analysis of the monthly data set to only the most recent year's demand allowed many of the issues encountered in the data quality analysis to be ignored. The only issue still to be dealt with to allow accurately representative monthly analysis was to input alternate data for the months missing from the Thomas Graham data set.

This was created by averaging the increase in monthly demand for each month from 2012-2013. This figure was then added to the 2012 demand of the missing months to generate demand representative of 2013. This process can be seen in Table 9:4 below.

Table 9:4 - Thomas Graham Monthly Data Generation

	Tomas Graham Data		
	2011	2012	Difference
MAR	213309	218488	5179
APR	203543	186973	-16570
MAY	179876	204452	24576
JUN	186841	192308	5467
JUL	181904	183385	1481
AUG	182483	193870	11387
SEP	194101	170536	-23565
OCT	192150	197233	5083
NOV	201679	207444	5765
DEC	180782	155716	-25066
JAN	169080	177231	8151
FEB	185215	209461	24246
		Average:	2178
		MAR 2013	**220666**
		APR 2013	**189151**
		MAY 2013	**206630**
		JUN 2013	**194486**

This monthly data was then substituted into the table in place of the missing months (March-June 2013) of the Thomas Graham building gas data for the monthly load demand analysis.

While not used in the load demand matching analysis, the monthly data for years 2010-11 and 2011-12 were assessed against the most recent 2012-13 year to briefly compare the development of demand on the campus. The issues identified with the earlier monthly data sets therefore had to be overcome to ensure the accuracy of this analysis.

The first step was replacing the missing year, from June 2011 until June 2012, from the Lord Hope gas data set. This was achieved by calculating the difference between the equivalent months from the 2010-11 and 2012-2013 data sets then either adding half of this difference to the 2011 value - or subtracting half of the difference from the 2013 value - to generate a representative value for that month in 2012. This process can be seen in Table 9:4 below. To generate the value for June 2011, it was required to subtract the entire average difference from the 2013 demand.

Table 9:5 - Lord Hope Monthly Data Generation

	Lord Hope % Difference between 2011 and 2013 readings			
	2010-11	**2012-13**	**Difference**	***2011-12**
AUG	8292.87	30438.98	22146.11	19365.93
SEP	34664.85	43180.14	8515.29	38922.50
OCT	89696.50	63801.12	-25895.38	76748.81
NOV	71649.17	74349.91	2700.74	72999.54
DEC	145331.84	110921.17	-34410.67	128126.51
JAN	112446.30	95955.87	-16490.43	104201.09
FEB	82896.98	106663.53	23766.55	94780.25
MAR	80609.29	105297.27	24687.98	92953.28
APR	7212.58	110603.44	103390.86	58908.01
MAY	6132.28	70632.42	64500.14	38382.35
		Average:	17291.12	
JUN		37047.86	2011	19756.74
JULY	81340.08		2011	72694.52
JUN		37047.86	2012	28402.30

This calculated data was then entered for each missing month. This same exercise was also performed for the Hamnett Wing electrical data. The data spike identified in June 2011 was assumed to be a manual data entry error. This was overcome by removing the last digit of the figure, which represented a more applicable figure.

- Data Profiling of Sports Centre & TIC Building

While the use of simulated data is in contravention to the stated goal of using only recorded data in the analytical load comparison, it was decided that these new developments represent such a potentially important part of the future energy demand on the campus site that it would be in the best interests of the project to include these sites for analysis even on a purely hypothetical basis.

For the electrical demand profile the Central substation data set was chosen for both sites as this represents the largest proportion of the campus electrical demand data to be met by the proposed energy network; the Central substation also provides the lowest percentage representation of domestic demand of the two substations supplying the campus. The Sir William Duncan building was chosen to represent the TIC building; its current office based use was thought to be the closest match available to the anticipated use of the TIC building. It was decided to represent the gas usage of the Sports Centre with the Curran Building profile; the Curran building gas demand profile was thought to be the most evenly applied throughout the year, a demand trait that is also anticipated from the Sports Centre.

- Heat to Power ratio of system

The analysis is based upon the assumption that the electrical generators to be installed in the proposed campus energy network system generate electricity and heat in a ratio of 1:1; that is for every unit of electricity generated, an equivalent measure of heat is generated concurrently.

This assumption is partially justified through the suggestion of a heat-to-power ratio of around 1:1.1 in previously commissioned reports on the energy network (Palmer & Tamburrini, 2007). The removal of the 0.1 from the heat generation in this ratio allows for both a more straightforward comparison in this analysis, while also making the results easier to interpret for a variety of alternate heat-to-power ratios that may be considered for the network in the future.

The 1:1 heat-to-power ratio is also the typical, characteristic ratio for a basic backpressure CHP generator as defined by (Marecki, 1988, p.35) (Harvey, 2006). Some more modern systems are listed as having larger conversion ratios although this ratio is also largely dependant on the system size (Harvey, 2006). As the scale of plant was to be a variable within this analysis, and in consideration of all the other factors mentioned, the use of a 1:1 heat-to-power ratio was assumed to be the most appropriate.

- Use of Gas as Heat

The assumption of using gas demand to directly represent the heat demand throughout the analysis was made as it was deicide that the inclusion of individual efficiencies would complicate the analysis to such an extent that the scope of the study would have to be restricted. This assumption is further justified by the work of (Dotzauer, 2002), where the simplification of analysis through justified means is affirmed.

- Use of Esp-r

Firstly, it must be stated that Esp-r is an incredibly powerful but also complex simulation software. Once the modelling process was started it became clear very quickly that some limitations would have to applied to the programs use to keep this section of the analysis within the original scope of the thesis. It was therefore decided that due to the complex nature of the program it would be more appropriate to generate a percentage demand profile from annual data rather than extracting a cooling demand profile from the simulation as was originally planned.

The EPC certificates used feature a percentage breakdown of the anticipated energy use for the building in question and while they may not be as accurate as genuine recorded energy usage, in the absence of recorded demand they afford an outline of how the building is expected to perform.

- Lithium Bromide Absorption Unit

A Lithium Bromide cycle unit was chosen over the ammonia equivalent as it requires lower input temp (70-90 ^{0}C for single effect system compared to 125-170 ^{0}C for ammonia) combined with a higher COP. Typical COP for this form of Absorption unit is around 0.7. Ammonia is also hazardous and the equipment used in lithium bromide chillers is also simpler, requiring a lower pressure condenser and no rectifier to separate any ammonia. (Florides et al, 2002b) in (Harvey, 2006).

Appendix 5 – Methodology: Processing of Daily Data in Excel

With daily demand totals available for each of the required data sets, the data must then be processed into a form that will facilitate the calculation of daily HPR for the relevant phases and comparison of the load demands. With only two data sets within the spreadsheet the daily electrical totals are easily separated for analysis; however, as with the monthly analysis, the gas data sets require more work. The gas consumption data is set out in one continuous column of rows sorted primarily by the building name followed the date with each row representing one day.

The first step in arranging the gas data set for analysis must therefore be to divide the building consumption data separate sheets for each phase in the analysis, as this separation should allow the data to be better sorted as required by the user. This separation can be achieved by assigning a phase number to each individual building data matrix, sorting the data for these numbers and then segregating the data set accordingly

For the purposes of this analysis the sheets were sorted first by date, by MPR number and then alphabetically by building name. This arrangement allows for the clear separation of each phase and a logical time step progression of the data within each phase. Sorting by MPR number before building name also allows the separate meters for some sites to be kept clearly separated, removing any confusion as to which meter the particular reading is taken from.

To facilitate ease of use, and to keep the spreadsheet within manageable dimensions, the next step was to hide the half-hourly consumption columns for each of the phases. The hiding of these cells must be performed after the arrangement into separate column clusters for each phase, as copying the columns while the cells are hidden will result in the loss of the half hourly data from the spreadsheet which means the sheet cannot be used in any following analysis of the half-hourly data.

The next step in processing the daily gas data is to ensure that any erroneous data in the set, such as missing data, double entries or any others identified in the data validation process, are accounted for. It is critical that this task be performed thoroughly to minimise complications further on in the process. Examples of the data issues encountered in this project can be found in the preceding chapter on data validation.

Once the data set has been adequately prepared the total daily consumption for each phase must be summed, much like the summation of the half-hourly data. However, as the half-hourly gas data set used in this project featured staggered start dates for many of the phases, this process required manually sifting through the phase column clusters to ensure the cells being counted were altered appropriately as the digital meter for another building in the phase became active. To make it clear to the user which data was being totalled, another row was added after each day to include the summed total.

Applying the same method used to filter for the daily electrical demand data, in each sheet the gas totals are filtered using the Total figure in the MPR column to display only the daily totals for that phase. This allows the daily gas consumption for each phase to be represented in a single column array.

These tables are then copied into one spreadsheet to allow ease of comparison and analysis. The final step in this data processing method, before analysis in the daily data can be undertaken, is to sort the column clusters for each phase by their start date. This is mainly for the purpose of arranging the daily data into such a form that the staggered start dates for various phases are clearly highlighted to prevent any misinterpretation of the data.

Lastly, the daily totals for both electrical and gas consumption are combined in one spreadsheet for the purpose of analysis. This final constructed data set allows for the high-level gas heating loads of each phase to be accurately compared with the electrical loads from the four progressive electrical demand phases, followed by the generation of the relevant HPR.

Appendix 6 – Methodology: Processing of Half-hourly Data in Excel

The first step in this processing method is to once again split the complete data set into the proposed Phases. As defined above with the daily data analysis, this can be achieved by assigning a Phase number to each set of building data then sorting and separating the data according to this factor.

Once the data is arranged in separate sheets for each phase the next step is to sum the half hourly demand for each building included in the phase, which represents the total demand for that phase at that time.

When the half-hourly demand totals have been achieved for the gas data set they should be copied into a new spreadsheet, with one phase to each sheet, to be processed further. As has been stated above, the analysis of data and columns and rows is a fairly straightforward process in Excel, however detailed analysis of data in matrix form is not as directly achievable.

With the half hourly demand for each day arrayed horizontally the data cannot be compared against the electrical equivalent and analysed as required for this project. The data could be manually transposed and copied into place, however with over three hundred rows and forty eight columns representing only the first phase of the process this would not only constitute a incredibly time consuming process but also likely generate unnecessary manual errors in the data set.

The solution to this issue is therefore to create a macro within excel that will not only automatically transpose the data but then also list the data in one column, in chronological order. The macro created and used for this purpose can be seen below Appendix 7.

This macro should be written in VBA code in Excel and applied to a selected data set, in this case the half hourly gas data. When run, the macro lists each of the selected rows from left to right in an ascending column, situated two cells to the right of the top right hand corner of that data selection, with each succeeding row listed below the last. An example of the data processing performed by the macro is shown in Appendix 5.

After this macro has been applied to each of the phased half-hourly gas data sets, the columns created are then copied into one final sheet along with the half-hourly electrical data. These data sets are then to be arranged chronologically but also, as with the daily analysis, into a form representing the staggered availability of the half-hourly gas data.

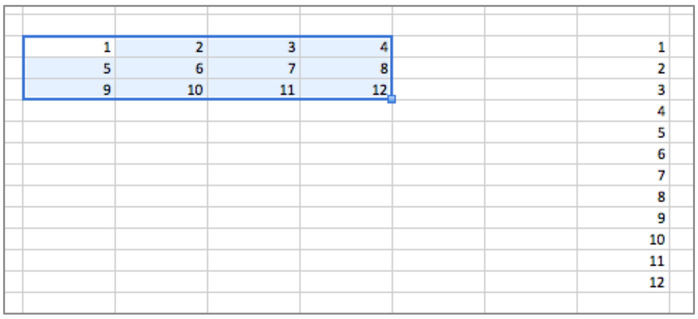
Appendix 7 – Methodology: Data Processing Excel Macro

The macro written for conversion of the gas demand data from its matrix form to a column is shown below in Figure 9:2.

```
Sub Gas_matrix_processor()
        Dim Outcell As Range
        ctr = 0

        Set Outcell = Selection.Cells(1, 1).Offset(0, Selection.Columns.Count + 2)

        For Each Cell In Selection
            Outcell.Offset(ctr, 0).Value = Cell.Value
            ctr = ctr + 1
        Next Cell

End Sub
```

Figure 9:2 – Macro used to Transpose Demand Data

The application of this macro is illustrated below in Figure 9:3.



1	2	3	4			1
5	6	7	8			2
9	10	11	12			3
						4
						5
						6
						7
						8
						9
						10
						11
						12

Figure 9:3 - Illustration of Macro in Use

Appendix 8 – Methodology: Storage Vessel Calculations

- Equation for Area of storage vessel (cylinder):

$$A = 2\pi \left(\frac{d}{2}\right)^2 + 2\pi \left(\frac{d}{2}\right) h$$

Equation 9:1

Where,

d = Diameter of storage vessel 4m

h = Height of storage vessel 8m

The dimensions of the storage vessel are illustrated below in figures 9:4.a, and 9:4.b.

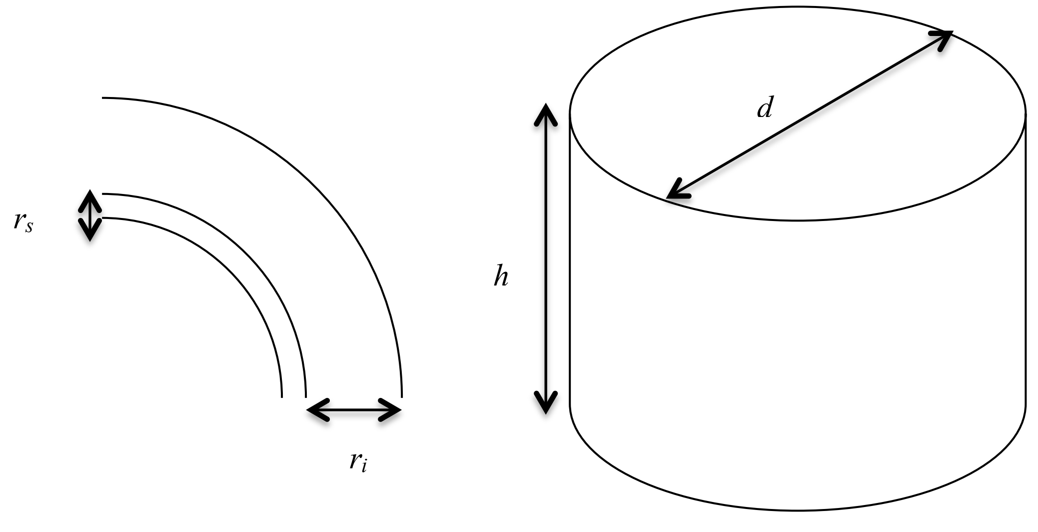


Fig.9:4.a. Material Thicknesses **Fig.9:4.b. Cylinder dimensions**

Figure 9:4 - Storage Vessel Dimensions

Where,

d = Cylinder Diameter = <u>4m</u>

h = Cylinder Height = <u>8m</u>

r_s = Steel thickness = <u>0.005m</u>

r_i = Material Wool thickness = <u>0.2m</u>

Which, when entered into the equation (Eq. 9:1) above, gives:

$$A = 2\pi(2)^2 + 2\pi(2)(8)$$

$$\underline{A = 135.66\, m^2}$$

- Equation for calculation of the U Value:

$$U = \frac{1}{\Sigma(R)}$$

Equation 9:2[18]

Where,

U = Overall Heat Transfer Coefficient (W/m^2K)

R = Thermal Resistance (m^2K/W)

The combined thermal resistance of the storage vessel must therefore be calculated before the U-value can be achieved; this is performed as follows.

- Thermal Resistance:

$$R = {}^{l}/_{\lambda}$$

Equation 9:3[19]

Where,

l = Thickness of material (m)

λ = Thermal conductivity (W/mK)

The respective value and symbol for each material property are shown below in Table 9:6.

[18] (ME928 - Energy Systems Analysis, 2012)

[19] (ME928 - Energy Systems Analysis, 2012)

Table 9:6 - Storage Vessel Material Properties

Material	Thermal Conductivity (W/mK)		Thickness (m)	
Galvanised Steel	50[20]	λ_s	0.005	r_s
Mineral Wool	0.038[21]	λ_i	0.2	r_i

The thermal resistance for each material in the storage vessel can therefore be calculated, as shown below:

$$R_s = {}^{r_1}/_{\lambda_s} \qquad R_i = {}^{r_2}/_{\lambda_i}$$

Equation 9:4

$$R_s = {}^{0.005}/_{50} \qquad R_i = {}^{0.2}/_{0.038}$$

$$\underline{R_s = 0.0001\ \mathrm{m^2K/W}} \qquad \underline{R_i = 5.2631\ \ \mathrm{m^2K/W}}$$

From here the overall U-value for the storage vessel can be calculated, as shown below with U_{sv} representing the U-value of the storage vessel:

$$U = \frac{1}{\Sigma(R)}$$

Equation 9:5

$$U_{sv} = \frac{1}{\Sigma(R_s + R_i)}$$

$$U_{sv} = \frac{1}{\Sigma(0.0001 + 5.2631)}$$

$$\underline{U_{sv} = 0.19\ W/m^2K}$$

[20] (Anderson, 2006)
[21] (CIBSE, 2006)

Appendix 9 – Methodology: Waste Heat Analysis - Application of Method

The analytical method employed in this section is based around the application of the formula defined section (4.2.3.1) above to the division of Heat supply phases. It is here that the real value of converting half-hourly into hourly demand data is established; with the demand given in units of kWh over intervals of 1 hour, it can be directly converted into an equal number of kW for the purposes of this analysis. The first step in arranging data sets for this purpose is to create three empty columns to represent the calculations required for each time step.

The next step in the process is to enter the calculated values and constants into the spreadsheet for use in the calculations to follow, as illustrated below in Table 9:7.

Table 9:7 - Data Required for Waste Heat Calculations

U-Value	Vessel Area	Mass	S.H.C	Internal T	External T
U (W/mK)	A (m2)	m (kg)	Cp (kJ/kGK)	T1 (K)	Te (K)
0.19	125.66	100000	4.187	383	291

Once this data has been entered into each spreadsheet, the formula required for the analysis can then be entered in to the three empty columns. The formulas are represented in Excel as shown below.

- The energy storage calculation (Eq. 4:4):

$$Q_{s2} = Q_{u2} - Q_{l2} - Q_{tl2} + Q_{s1}$$

This calculation is entered in to the first free column. The first row of each phase will not consider any heat to be already available from the storage vessel and as such will not include the Q_{s1} term; however, all other rows in this column will include the heat previously stored in the equation. The first cell in the column is therefore input as:

=D9–E9–R9

Equation 9:6

Where,

D9 = Heat generated at this time step

E9 = Heat demand at this time step

R9 = Losses for this time step

The second cell in the column is entered as:

= Q9+D10– E10– R10

Equation 9:7

Where,

Q9 = Heat stored in previous time step (as calculated in Eq. 4.7)

The formula is entered into the second cell of the column is then copied to all other cells in the column to calculate the heat stored at each time step.

- The energy losses calculation (Eq. 4:5):

$$Q_{tl} = (U.A)_s(T_s - T_e)$$

This calculation is entered in to the second free column. The first row of each phase will consider the heat of the fluid in the storage vessel to be the assumed starting internal temperature of 383K. All subsequent loss calculations will consider the temperature of the fluid as that calculated for the previous time step combined with the temperature variation caused by the energy balance calculation; thereby representing the continuous change in the amount of thermal energy stored in the vessel. The input into the second column is therefore input as:

=(($C$3*$D$3)*($G$3–$H$3))/1000

Equation 9:8

Where,

$C$3 = U-value for the storage vessel

$D$3 = Fluid contact area

$G$3 = Initial temperature of the fluid in the storage vessel

$H$3 = External temperature

The division of the result by one thousand represents the conversion from Watts (W) to kilowatts (kW) as required by the analysis.

The second cell in the second column is entered as:

```
=(($C$3*$D$3)*(R8-$H$3))/1000
```

Equation 9:9

Where,

R8 = Temperature of the fluid calculated for the previous time step

The formula entered into the second cell of the column (Eq. 4:10), is then copied to all other cells in the column to calculate the heat losses from the vessel for each time step.

- The temperature change calculation (Eq. 4.6):

$$\frac{dT_s}{dt} = \frac{(Q_u - Q_l - Q_{tl})}{(m.C_p)_s}$$

This calculation is entered in to the third free column. The first row of each phase will consider the heat of the fluid in the storage vessel to be the assumed starting internal temperature of 383K. All subsequent temperature change calculations will consider the temperature of the fluid as that calculated for the previous time step. The input into the third column is therefore entered as:

```
=(D8-Q8-E8)/($E$3*$F$3)+$G$3
```

Equation 9:10

Where,

D8 = Heat generated at this time step

Q8 = Heat losses at this time step

E8 = Heat demand at this time step

$E$3 = Fluid contact area

$F$3 = Specific heat capacity of fluid

$G$3 = Initial temperature of the fluid in the storage vessel

The second cell in the third column is entered as:

=(D9–Q9–E9)/($E$3*$F$3)+R8

Equation 9:11

Where,

R8 = Temperature of the fluid calculated for the previous time step

The input of these values and formula is then extended to each heat supply phase to complete the potential waste heat use analysis for all iterations of the proposed energy network.

To conclude as to the most appropriate combination for this purpose, the heat storage (Q_s) columns should then be collected and analysed as these most accurately demonstrate the heat storage performance over the course of the analysis.

Appendix 10 – Methodology: Detailed Definition of Esp-r Model

Weekday				Saturday/Sunday			
Time Frame	Occupation	Gain Type	Gain (W/m2)	Time Frame	Occupation	Gain Type	Gain (W/m2)
00:00 - 08:00	Unoccupied	People	0 (S) 0 (L)	00:00 - 09:00	Unoccupied	People	0 (S) 0 (L)
		Equipment	8			Equipment	8
		Lighting	0			Lighting	0
08:00 - 18:00	Full	People	20.25 (S) 14.85 (L)	09:00 - 17:00	Half	People	10.13 (S) 7.43 (L)
		Equipment	37.7			Equipment	22.85
		Lighting	4.2			Lighting	4.2
18:00 - 21:00	Half	People	10.13 (S) 7.43 (L)	17:00 - 24:00	Unoccupied	People	0 (S) 0 (L)
		Equipment	22.85			Equipment	8
		Lighting	4.2			Lighting	0
21:00 - 24:00	Unoccupied	People	0				
		Equipment	8				
		Lighting	0				

Table 9:8 – Simulated Gains for Esp-r Model

Appendix 11 – Methodology: Esp-r Results Profiling

To create the demand profile the temperature results file required processing into a form from which the profile could be generated. The original results file arrays the results in columns with the results separated for each day and lists the time step as a decimal function. These factors are overcome by deleting the rows separating the daily results sets and changing the style of the time-step column to represent time. With the data set now arrayed in a form conducive to the profiling methodology, the process can be undertaken as defined below.

The column to the right of the temperature profile is used to assess the whether cooling is required at that time-step and also determining the degree of cooling required. An IF function is used to determine whether the temperature in the zone is above the minimum cooling threshold, assumed to be 18^{o}C. If the temperature is below this threshold the cell displays a zero (0) value, to represent no cooling demand. If the temperature is above this threshold the cell will display a value equal to the temperature minus the threshold (18), representing the proportional demand for cooling. The formula used for this process is entered into Excel as:

```
=IF(E8>18,(E8-18),0)
```

Equation 9:12

Where,

E8 = Temperature recorded in the zone for that time step

This formula is copied down for each cell in the column to generate the foundation of the profile. Through application of the same method defined in the Data Profiling & Analysis section (4.1.5) above, the summed total for this column of data is then divided by each time step in turn to create demand load profile for the cooling demand. The application of this method cab be seen below in Figure 9:5.

53.04	% Profile	
Unit_hidbT(degC)	Deg > 18	% of Load
19.25	1.25	3.56764E-06
19.21	1.21	3.45347E-06
19.16	1.16	3.31077E-06
19.12	1.12	3.1966E-06
19.07	1.07	=G27739/$G$27744
19.03	1.03	2.93973E-06
18.99	0.99	2.82557E-06
18.95	0.95	2.7114E-06
18.92	0.92	2.62578E-06
TOTAL =	350372.1	

Figure 9:5 - Cooling Demand Profiling

This demand profile can now be combined with the total annual cooling requirement, calculated using EPC data as defined above, to generate the cooling profiles required for analysis.

As with the profiles developed in the section (4.1.5) above, the generated percentage profile is multiplied by the annual total to generate a representative cooling demand for each time step. For the purposes of this analysis these were collected into profiles illustrating the cooling demand for each phase.

Appendix 12 – Methodology: Waste Heat for Cooling – Application of Method

With yearly cooling demand profiles achieved for each phase and the appropriate formula derived to calculate the heat required to meet this demand, it is now possible to quantify and profile the resultant heat load. Profiling this heat demand also provides the opportunity to investigate the impact this additional heat requirement could have on other aspects of the proposed energy network.

The analytical method employed in this section is based around the application of the formula defined in the preceding section (4.2.4.2) to the cooling demand profiles. The first step in the preparing the spreadsheet for this analysis is to insert a blank column to separate the cooling demand phase totals.

The next step in the process is to enter the required constant values into the spreadsheet for use in the calculations to follow. In this case there is only one constant necessary, the coefficient of performance of the absorption chiller (COP_{ABS}), which is taken to be 0.7 as stated in the assumptions above. Once this value has been entered into the spreadsheet, the formula required for the analysis is input to the empty column to the right of the heating total for the first phase. The formula is represented in Excel as shown below.

- Heat Demand Formula (Eq. 4.17):

$$\Delta H = \frac{Q_{Ch}}{COP_{ABS}}$$

This formula is input to Excel as follows:

=D6/$B$2

Equation 9:13

Where,

D6 = Profiled cooling demand

$B$2= Coefficient of performance for Absorption Chiller (COP_{ABS})

This formula is then copied to each cell in that column, followed by the columns to the right of all the other phased cooling load profiles. This will calculate the heating demand for each time step in the profile, which can then be analysed in conjunction with the waste heat calculations in the Demand Matching section (4.2.3) above to assess the viability of using absorption chillers in each phase.

Appendix 13 – Monthly Analysis: Total Demand for Heat and Power

	ELECTRICITY				GAS (Heat)									
MONTH	Central Sub	C + SC	C, SC + GH	C, SC, GH+ TIC	Phase 1	Phase 1-2	Phase 1-3	Phase 1-4	Phase 1-5	Phase 1-6	Phase 1-7	Phase 1-8	Phase 1-9	Phase 1-10
JUL 2012	2173505	2243194	2440794	2548466	710456	1123835	1223318	1428956	1865287	1943554	1981295	1992981	2149910	2168500
AUG 2012	2282875	2353433	2565484	2674497	271472	605587	762928	890689	1263413	1345815	1352275	1353578	1371371	1400773
SEP 2012	2195315	2261710	2474177	2576760	786383	1354864	1527302	1716894	2150667	2251017	2475087	2516636	2716364	2748586
OCT 2012	2531552	2621929	2902711	3042347	1399010	2120145	2378843	2693495	3371402	3548896	4071676	4182774	4567550	4615892
NOV 2012	2738618	2836526	3143601	3294873	1262639	2144599	2466543	2890115	3692713	3906152	4541772	4685364	5183064	5243224
DEC 2012	2379629	2458709	2755244	2877425	1503785	2500519	2770071	3270630	4071150	4266178	4987815	5142671	5682852	5733222
JAN 2013	2605097	2697456	2999787	3142485	1803822	2686424	3015224	3480006	4285302	4495937	5156382	5294692	5896164	5957605
FEB 2013	2564099	2662207	2950895	3102473	1616986	2505151	2820322	3322692	4079493	4287109	4934735	5057430	5509726	5568620
MAR 2013	2433954	2522349	2823715	2960288	1776913	2659930	2950618	3438563	4234665	4426488	5089163	5217162	5735451	5789771
APR 2013	2277066	2357534	2632387	2756712	1821807	2715143	3040025	3568386	4448004	4665362	5438325	5585934	6006425	6067134
MAY 2013	2322244	2395775	2746055	2859662	1372195	2003804	2216801	2606947	3318022	3482371	3946021	4044813	4279778	4319579
JUN 2013	2004633	2068453	2199354	2297957	908687	1540908	1683396	1893006	2251633	2363938	2412464	2423543	2469869	2496495

Table 9:8 - Total Monthly Demand

Appendix 14 – Monthly Analysis: Total Demand Profile

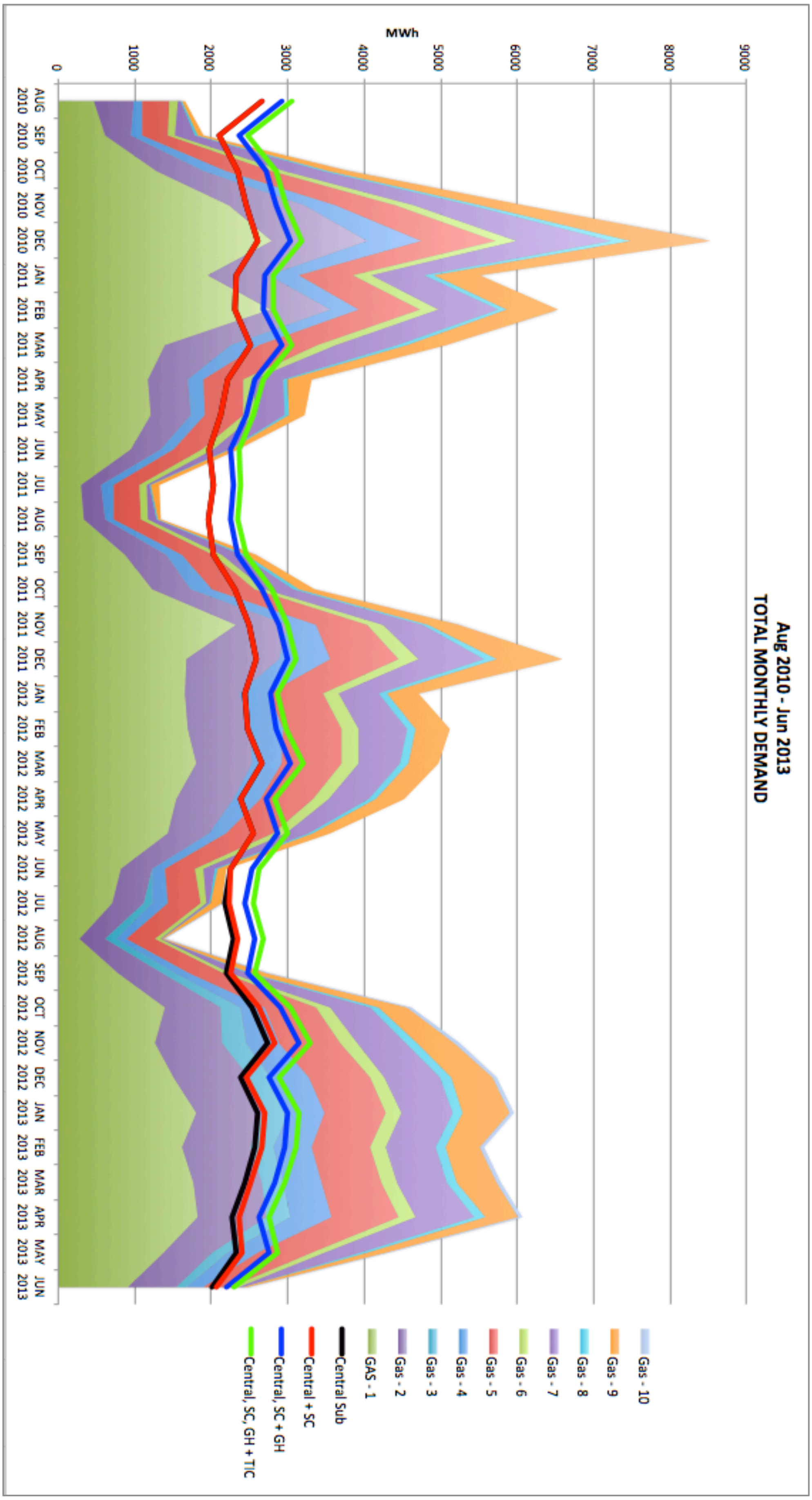


Figure 9:5 - Total Monthly Demand

Appendix 15 – Monthly Analysis: Tables of HPR Results

	Heat to Power Ratios - All Heating Phased vs Electrical Phase 1									
	P1 - E1	P2 - E1	P3 - E1	P4 - E1	P5 - E1	P6 - E1	P7 - E1	P8 - E1	P9 - E1	P10 - E1
JUL 2012	0.3269	0.5171	0.5628	0.6574	0.8582	0.8942	0.9116	0.9169	0.9891	0.9977
AUG 2012	0.1189	0.2653	0.3342	0.3902	0.5534	0.5895	0.5924	0.5929	0.6007	0.6136
SEP 2012	0.3582	0.6172	0.6957	0.7821	0.9797	1.0254	1.1274	1.1464	1.2373	1.2520
OCT 2012	0.5526	0.8375	0.9397	1.0640	1.3318	1.4019	1.6084	1.6523	1.8042	1.8233
NOV 2012	0.4610	0.7831	0.9007	1.0553	1.3484	1.4263	1.6584	1.7109	1.8926	1.9146
DEC 2012	0.6319	1.0508	1.1641	1.3744	1.7108	1.7928	2.0960	2.1611	2.3881	2.4093
JAN 2013	0.6924	1.0312	1.1574	1.3358	1.6450	1.7258	1.9793	2.0324	2.2633	2.2869
FEB 2013	0.6306	0.9770	1.0999	1.2959	1.5910	1.6720	1.9245	1.9724	2.1488	2.1718
MAR 2013	0.7301	1.0928	1.2123	1.4127	1.7398	1.8186	2.0909	2.1435	2.3564	2.3788
APR 2013	0.8001	1.1924	1.3351	1.5671	1.9534	2.0488	2.3883	2.4531	2.6378	2.6645
MAY 2013	0.5909	0.8629	0.9546	1.1226	1.4288	1.4996	1.6992	1.7418	1.8429	1.8601
JUN 2013	0.4533	0.7687	0.8398	0.9443	1.1232	1.1792	1.2034	1.2090	1.2321	1.2454

Table 9:9 - HPR for Electrical Demand Stage 1

	Heat to Power Ratios - All Heating Phased vs Electrical Phase 2									
	P1 - E2	P2 - E2	P3 - E2	P4 - E2	P5 - E2	P6 - E2	P7 - E2	P8 - E2	P9 - E2	P10 - E2
JUL 2012	0.3167	0.5010	0.5453	0.6370	0.8315	0.8664	0.8832	0.8885	0.9584	0.9667
AUG 2012	0.3167	0.2573	0.3242	0.3785	0.5368	0.5719	0.5746	0.5752	0.5827	0.5952
SEP 2012	0.3167	0.5990	0.6753	0.7591	0.9509	0.9953	1.0943	1.1127	1.2010	1.2153
OCT 2012	0.3167	0.8086	0.9073	1.0273	1.2858	1.3535	1.5529	1.5953	1.7421	1.7605
NOV 2012	0.3167	0.7561	0.8696	1.0189	1.3018	1.3771	1.6012	1.6518	1.8273	1.8485
DEC 2012	0.3167	1.0170	1.1266	1.3302	1.6558	1.7351	2.0286	2.0916	2.3113	2.3318
JAN 2013	0.3167	0.9959	1.1178	1.2901	1.5886	1.6667	1.9116	1.9628	2.1858	2.2086
FEB 2013	0.3167	0.9410	1.0594	1.2481	1.5324	1.6104	1.8536	1.8997	2.0696	2.0917
MAR 2013	0.3167	1.0545	1.1698	1.3632	1.6789	1.7549	2.0176	2.0684	2.2739	2.2954
APR 2013	0.3167	1.1517	1.2895	1.5136	1.8867	1.9789	2.3068	2.3694	2.5478	2.5735
MAY 2013	0.3167	0.8364	0.9253	1.0881	1.3849	1.4535	1.6471	1.6883	1.7864	1.8030
JUN 2013	0.3167	0.7450	0.8138	0.9152	1.0886	1.1429	1.1663	1.1717	1.1941	1.2069

Table 9:10 - HPR for Electrical Demand Stage 2

	Heat to Power Ratios - All Heating Phased vs Electrical Phase 3									
	P1 - E3	P2 - E3	P3 - E3	P4 - E3	P5 - E3	P6 - E3	P7 - E3	P8 - E3	P9 - E3	P10 - E3
JUL 2012	0.2911	0.4604	0.5012	0.5854	0.7642	0.7963	0.8117	0.8165	0.8808	0.8884
AUG 2012	0.1058	0.2361	0.2974	0.3472	0.4925	0.5246	0.5271	0.5276	0.5345	0.5460
SEP 2012	0.3178	0.5476	0.6173	0.6939	0.8692	0.9098	1.0004	1.0172	1.0979	1.1109
OCT 2012	0.4820	0.7304	0.8195	0.9279	1.1615	1.2226	1.4027	1.4410	1.5735	1.5902
NOV 2012	0.4017	0.6822	0.7846	0.9194	1.1747	1.2426	1.4448	1.4904	1.6488	1.6679
DEC 2012	0.5458	0.9075	1.0054	1.1871	1.4776	1.5484	1.8103	1.8665	2.0626	2.0808
JAN 2013	0.6013	0.8955	1.0051	1.1601	1.4285	1.4988	1.7189	1.7650	1.9655	1.9860
FEB 2013	0.5480	0.8489	0.9558	1.1260	1.3825	1.4528	1.6723	1.7139	1.8671	1.8871
MAR 2013	0.6293	0.9420	1.0449	1.2177	1.4997	1.5676	1.8023	1.8476	2.0312	2.0504
APR 2013	0.6921	1.0314	1.1549	1.3556	1.6897	1.7723	2.0659	2.1220	2.2817	2.3048
MAY 2013	0.4997	0.7297	0.8073	0.9493	1.2083	1.2681	1.4370	1.4730	1.5585	1.5730
JUN 2013	0.4132	0.7006	0.7654	0.8607	1.0238	1.0748	1.0969	1.1019	1.1230	1.1351

Table 9:11 - HPR for Electrical Demand Stage 3

	Heat to Power Ratios - All Heating Phased vs Electrical Phase 4									
	P1 - E4	P2 - E4	P3 - E4	P4 - E4	P5 - E4	P6 - E4	P7 - E4	P8 - E4	P9 - E4	P10 - E4
JUL 2012	0.2788	0.4410	0.4800	0.5607	0.7319	0.7626	0.7774	0.7820	0.8436	0.8509
AUG 2012	0.1015	0.2264	0.2853	0.3330	0.4724	0.5032	0.5056	0.5061	0.5128	0.5238
SEP 2012	0.3052	0.5258	0.5927	0.6663	0.8346	0.8736	0.9605	0.9767	1.0542	1.0667
OCT 2012	0.4598	0.6969	0.7819	0.8853	1.1082	1.1665	1.3383	1.3749	1.5013	1.5172
NOV 2012	0.3832	0.6509	0.7486	0.8772	1.1207	1.1855	1.3784	1.4220	1.5731	1.5913
DEC 2012	0.5226	0.8690	0.9627	1.1367	1.4149	1.4826	1.7334	1.7872	1.9750	1.9925
JAN 2013	0.5740	0.8549	0.9595	1.1074	1.3637	1.4307	1.6409	1.6849	1.8763	1.8958
FEB 2013	0.5212	0.8075	0.9091	1.0710	1.3149	1.3818	1.5906	1.6301	1.7759	1.7949
MAR 2013	0.6002	0.8985	0.9967	1.1616	1.4305	1.4953	1.7191	1.7624	1.9375	1.9558
APR 2013	0.6609	0.9849	1.1028	1.2944	1.6135	1.6924	1.9728	2.0263	2.1788	2.2009
MAY 2013	0.4798	0.7007	0.7752	0.9116	1.1603	1.2178	1.3799	1.4144	1.4966	1.5105
JUN 2013	0.3954	0.6706	0.7326	0.8238	0.9798	1.0287	1.0498	1.0547	1.0748	1.0864

Table 9:12 - HPR for Electrical Demand Stage 4

Appendix 16 – Monthly Analysis: Graphs of HPR for Staged Expansion

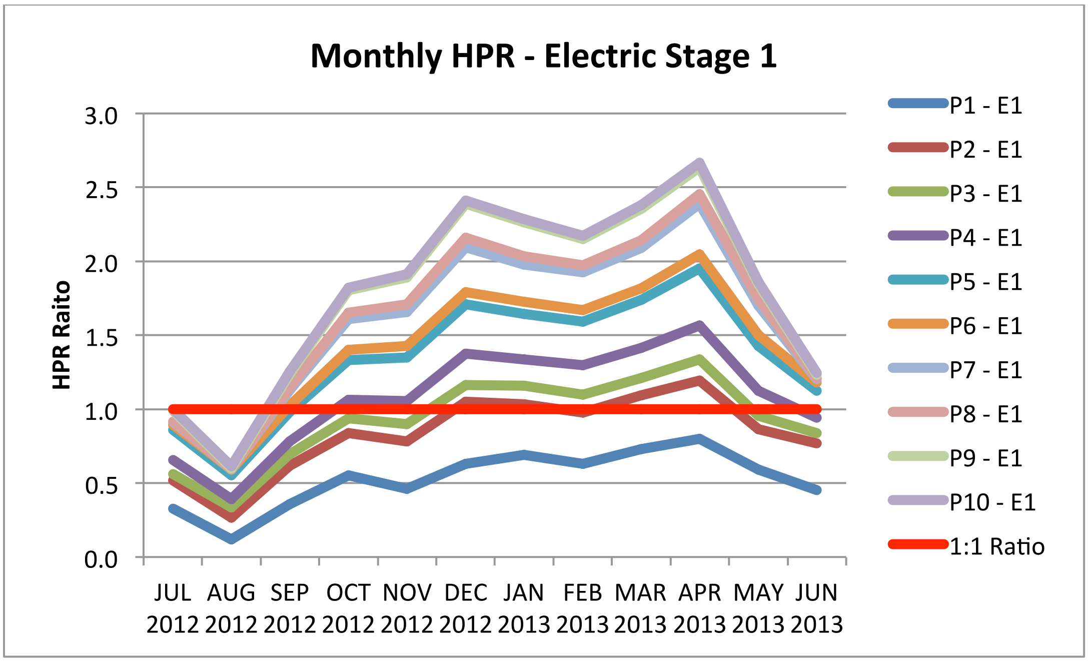


Figure 9:5 - HPR for Monthly Electrical Demand Stage 1

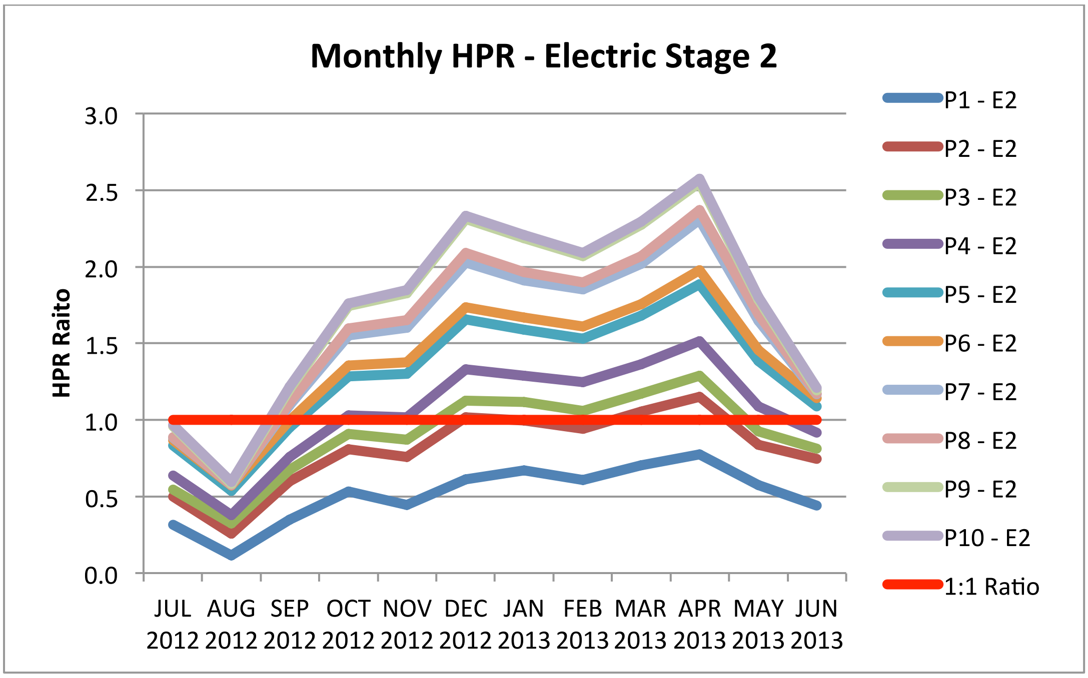


Figure 9:6 - HPR for Monthly Electrical Demand Stage 2

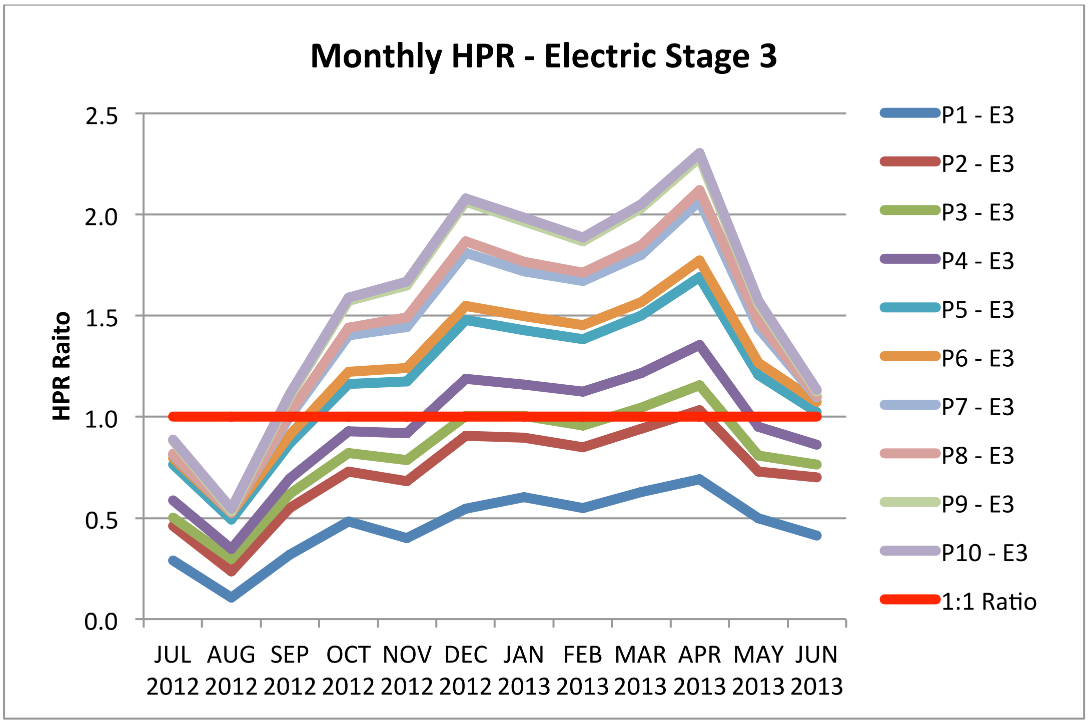


Figure 9:7 - HPR for Monthly Electrical Demand Stage 3

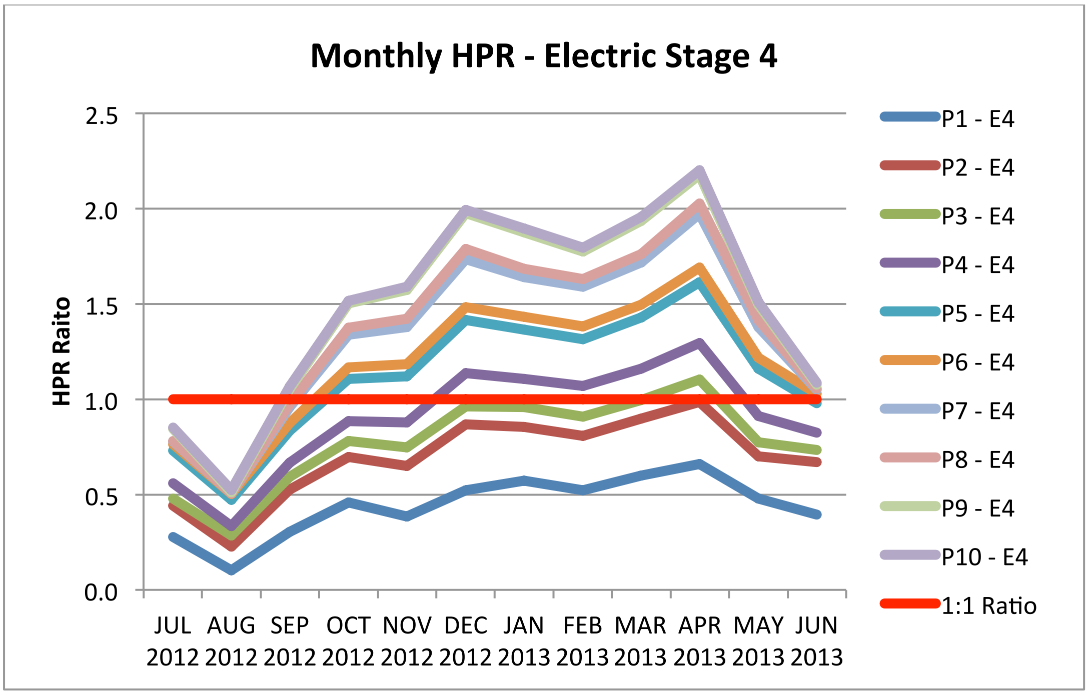


Figure 9:8 - HPR for Monthly Electrical Demand Stage 4

Appendix 17 – Monthly Analysis: Summary of HPR Results

HEAT TO POWER RATIO 1 (Central)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.8001	1.1924	1.3351	1.5671	1.9534	2.0488	2.3883	2.4531	2.6378	2.6645
0.1189	0.2653	0.3342	0.3902	0.5534	0.5895	0.5924	0.5929	0.6007	0.6136
0.5289	0.8330	0.9330	1.0835	1.3553	1.4228	1.6067	1.6444	1.7828	1.8015
HEAT TO POWER RATIO 2 (Central & Sports Centre)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.7728	1.1517	1.2895	1.5136	1.8867	1.9789	2.3068	2.3694	2.5478	2.5735
0.1154	0.2573	0.3242	0.3785	0.5368	0.5719	0.5746	0.5752	0.5827	0.5952
0.5113	0.8053	0.9020	1.0474	1.3102	1.3756	1.5532	1.5896	1.7234	1.7414
HEAT TO POWER RATIO 3 (Central, Sports Centre & Graham Hills)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.6921	1.0314	1.1549	1.3556	1.6897	1.7723	2.0659	2.1220	2.2817	2.3048
0.1058	0.2361	0.2974	0.3472	0.4925	0.5246	0.5271	0.5276	0.5345	0.5460
0.4606	0.7260	0.8132	0.9442	1.1810	1.2399	1.3992	1.4319	1.5521	1.5684
HEAT TO POWER RATIO 4 (Central, Sports Centre, Graham Hills & TIC Building)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.6609	0.9849	1.1028	1.2944	1.6135	1.6924	1.9728	2.0263	2.1788	2.2009
0.1015	0.2264	0.2853	0.3330	0.4724	0.5032	0.5056	0.5061	0.5128	0.5238
0.4402	0.6939	0.7773	0.9024	1.1288	1.1851	1.3372	1.3685	1.4833	1.4989

Table 9:8 – Monthly Analysis: HPR Summary Results

Appendix 18 – Daily Analysis: Phased Load Profile Graph

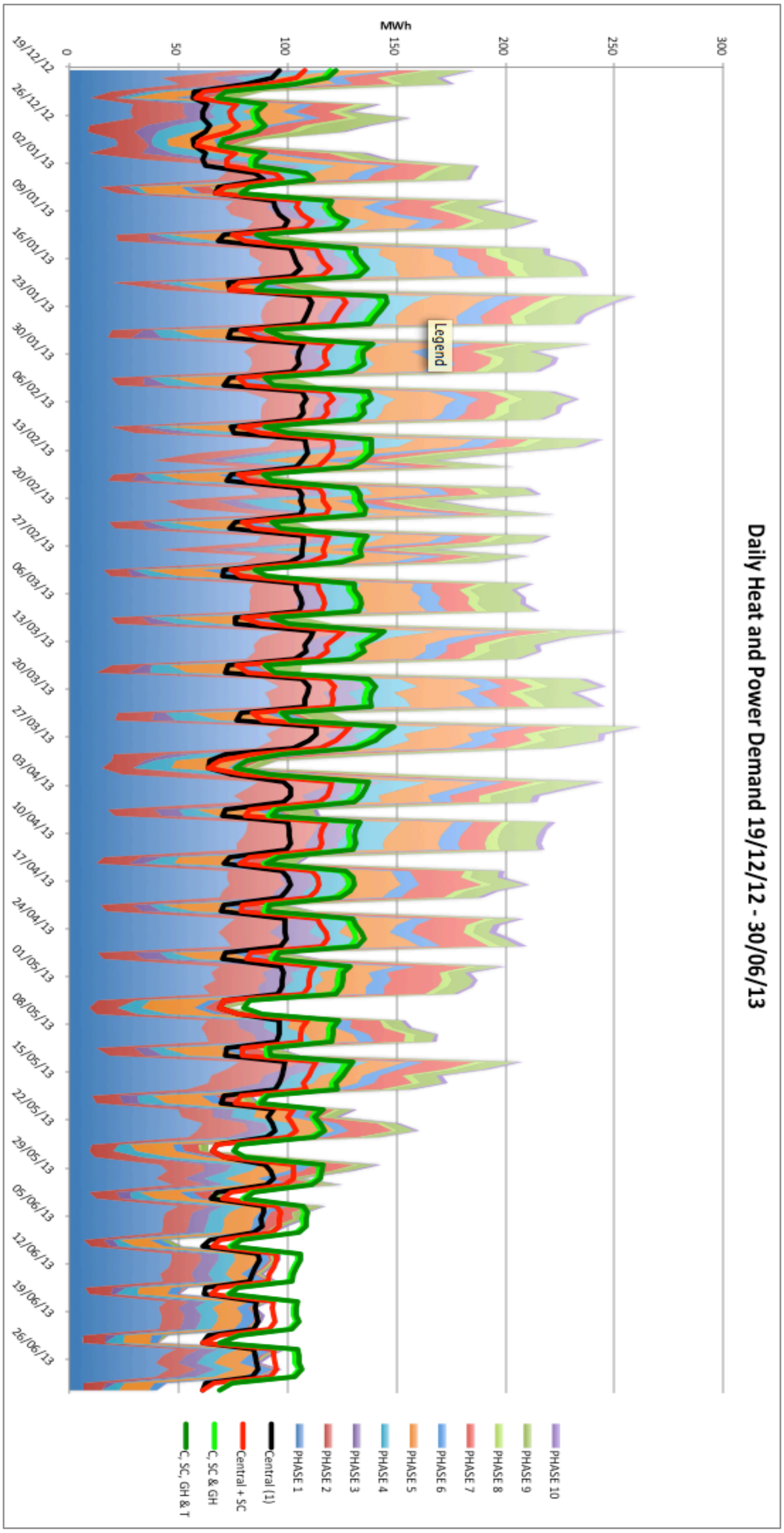


Figure 9:9 - Phased Daily Load Demand Profile

Appendix 19 – Daily Analysis: Full HPR Results Table

HEAT TO POWER RATIO 1 (Central)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	Max/Min/Mean
1.188346087	1.531166304	1.686855114	1.946654475	2.278146718	2.408229252	2.722827518	2.809270399	2.962346481	2.996153744	1.1883
0.100189945	0.242498461	0.247266119	0.366954082	0.583282903	0.655019838	0.660228452	0.660228452	0.660228452	0.660228452	0.6602
0.557330349	0.773886579	0.879638355	1.038687784	1.294054102	1.383570204	1.502852973	1.540560162	1.675699723	1.694795055	1.0387
HEAT TO POWER RATIO 2 (Central & Sports Centre)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	
1.028257846	1.32489498	1.459610147	1.684410593	1.971245804	2.083804247	2.356021355	2.43081907	2.563273481	2.592526394	1.0283
0.092456961	0.225859857	0.247266119	0.341776175	0.543261976	0.612552093	0.619163591	0.619256086	0.649139462	0.660228452	0.6602
0.500340812	0.695603246	0.790000193	0.933156954	1.164520252	1.245307947	1.3525237	1.386331241	1.508212539	1.525319941	1.1645
HEAT TO POWER RATIO 3 (Central, Sports Centre & Graham Hills)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	
0.894918492	1.153089201	1.270335176	1.465984621	1.715624471	1.813586896	2.050504247	2.115602566	2.230880949	2.25634049	0.8949
0.082764052	0.200408043	0.21959666	0.303261923	0.482042586	0.543524502	0.54939096	0.549473032	0.581085637	0.586347873	0.5863
0.445678506	0.619015346	0.703051348	0.83007306	1.034789317	1.106449184	1.201729745	1.23175452	1.33972663	1.354964465	1.0348
HEAT TO POWER RATIO 4 (Central, Sports Centre, Graham Hills & TIC Building)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	
0.872699952	1.124460942	1.238795999	1.429587968	1.673029898	1.768560167	1.999595464	2.063077559	2.175493874	2.20032132	0.8727
0.081709124	0.198153735	0.21959666	0.299850654	0.476620286	0.537410618	0.543211086	0.543292235	0.573679	0.586347873	0.5863
0.437917978	0.608529051	0.691157173	0.816201712	1.01805617	1.088634924	1.182292743	1.211786822	1.318053425	1.333045746	1.0181

Table 9:14 - Complete Daily HPR Assessment

Appendix 20 – Daily Analysis: HPR Graphs for Staged Expansion

Figure 9:10 - Daily HPR for Electrical Stage 1

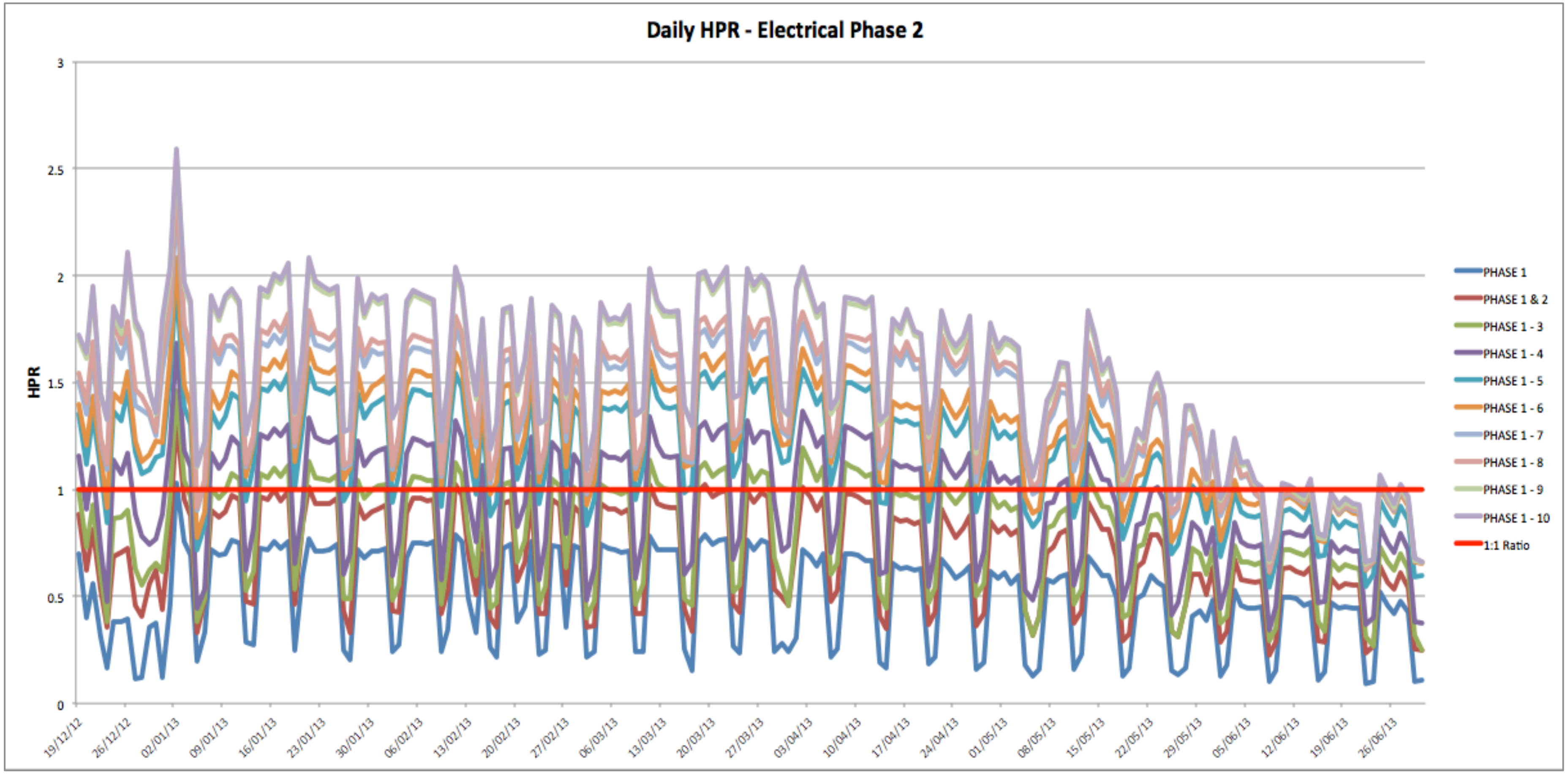


Figure 9:11 - Daily HPR for Electrical Stage 2

mm

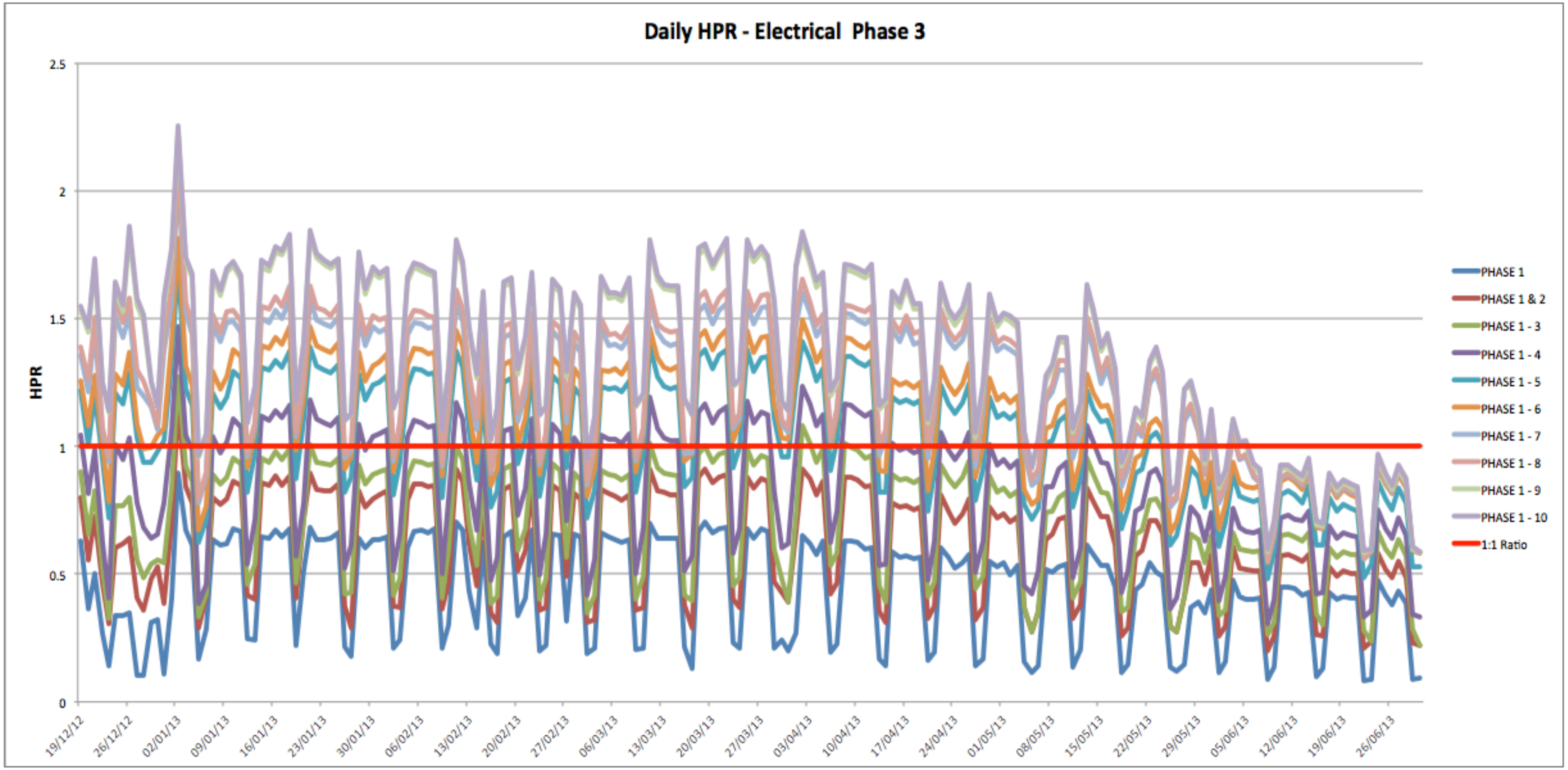


Figure 9:12 - Daily HPR for Electrical Stage 3

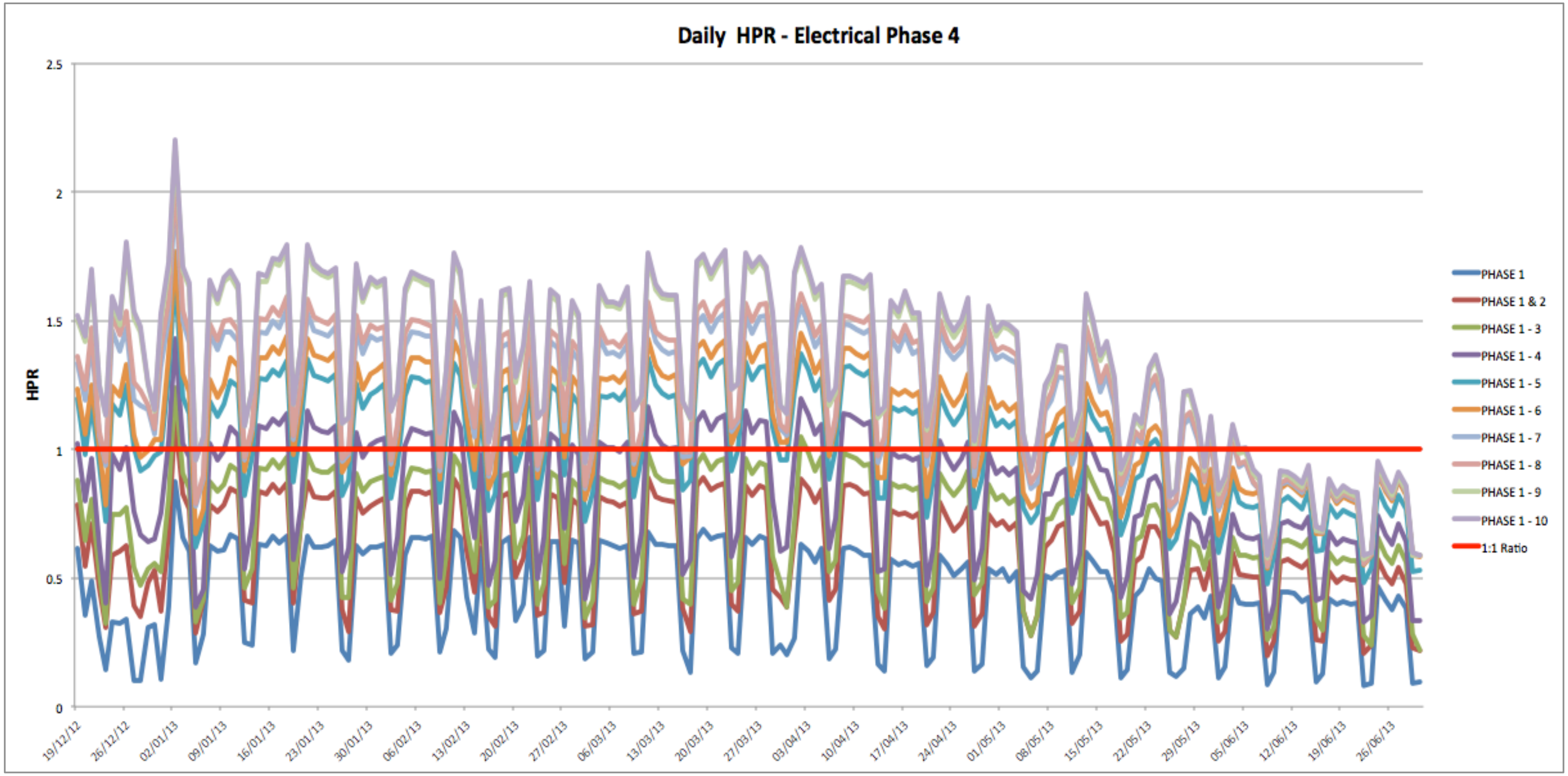


Figure 9:13 - Daily HPR for Electrical Stage 4

Appendix 21 – Half-hourly Analysis: Graphs of Monthly Demand Profiles

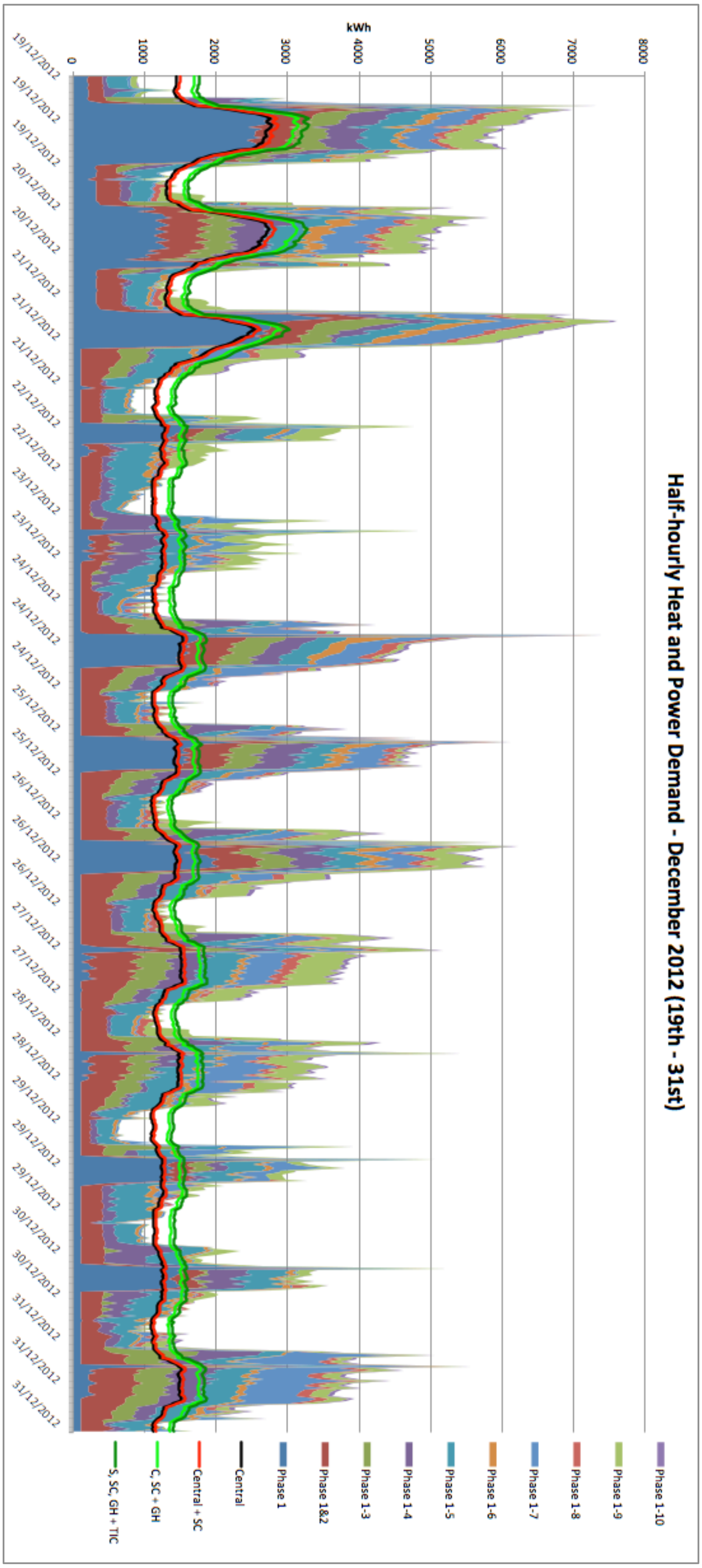


Figure 9:14 - Half-hourly Demand Profile - December

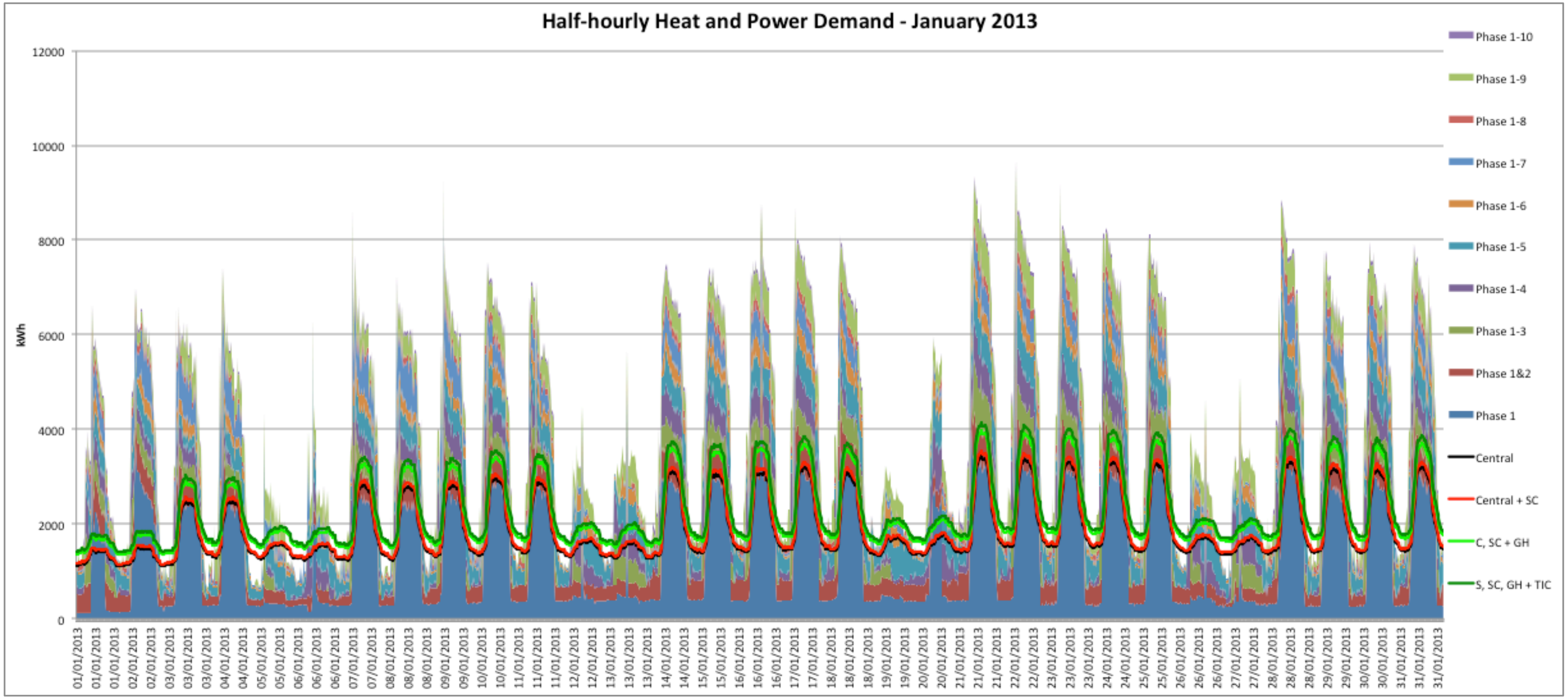


Figure 9:15 – Half-hourly Demand Profile - January

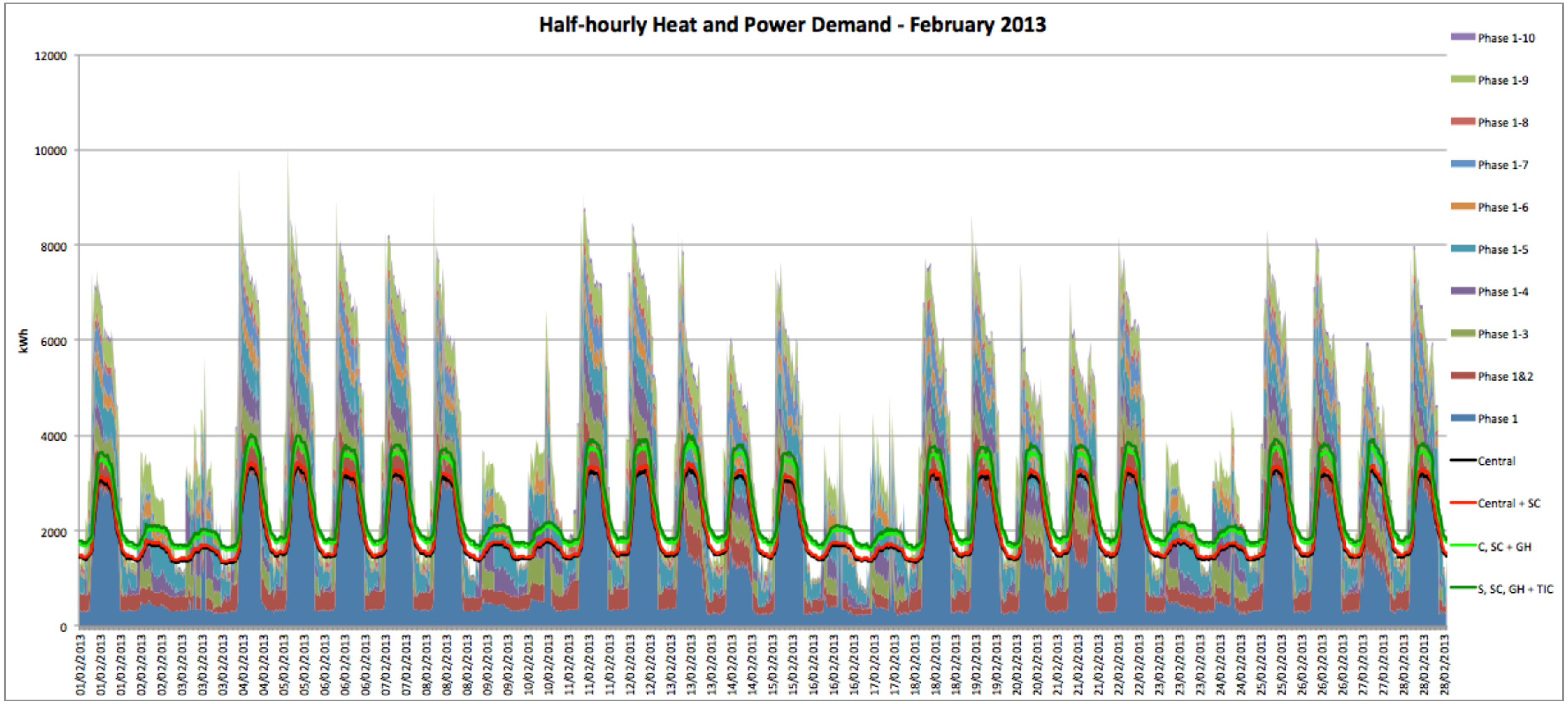


Figure 9:16 – Half-hourly Demand Profile - February

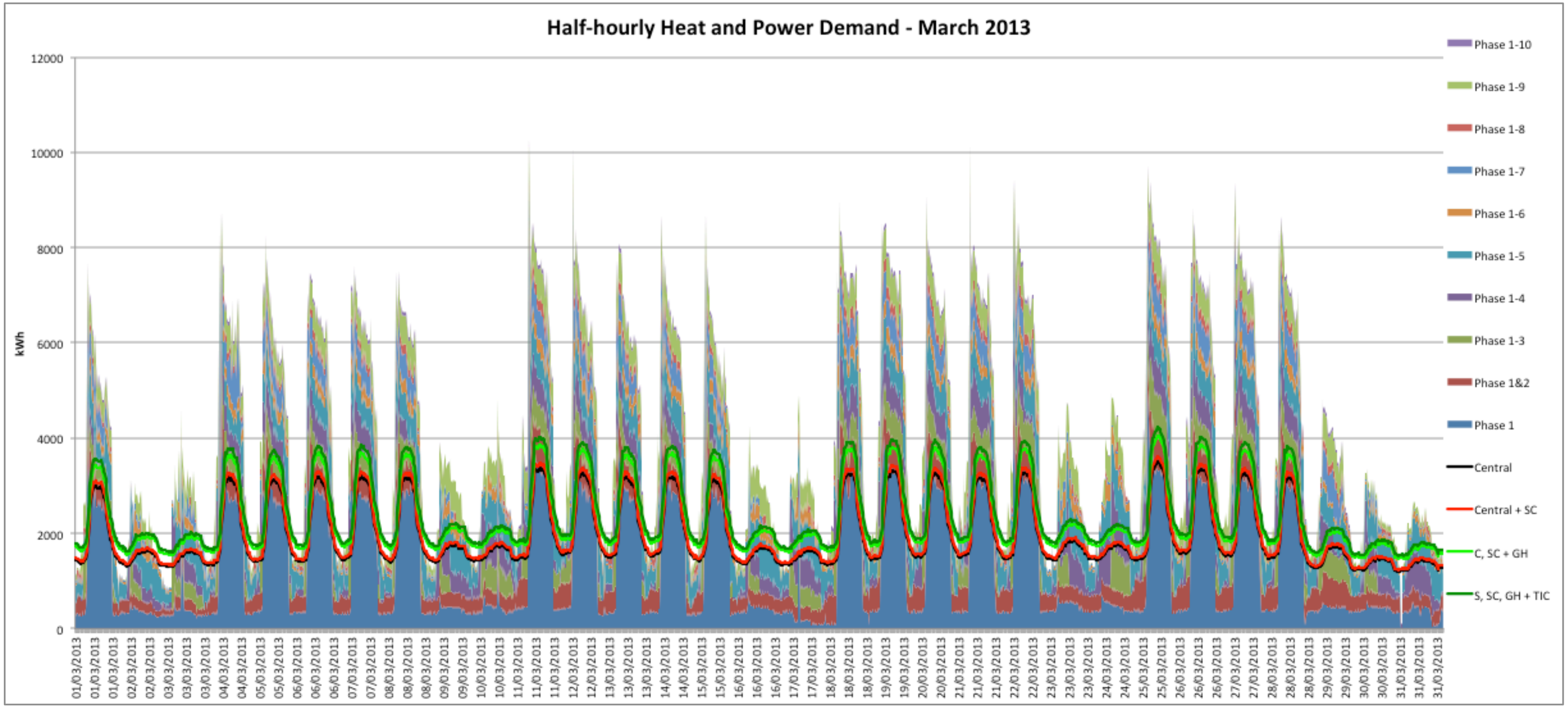


Figure 9:17– Half-hourly Demand Profile - March

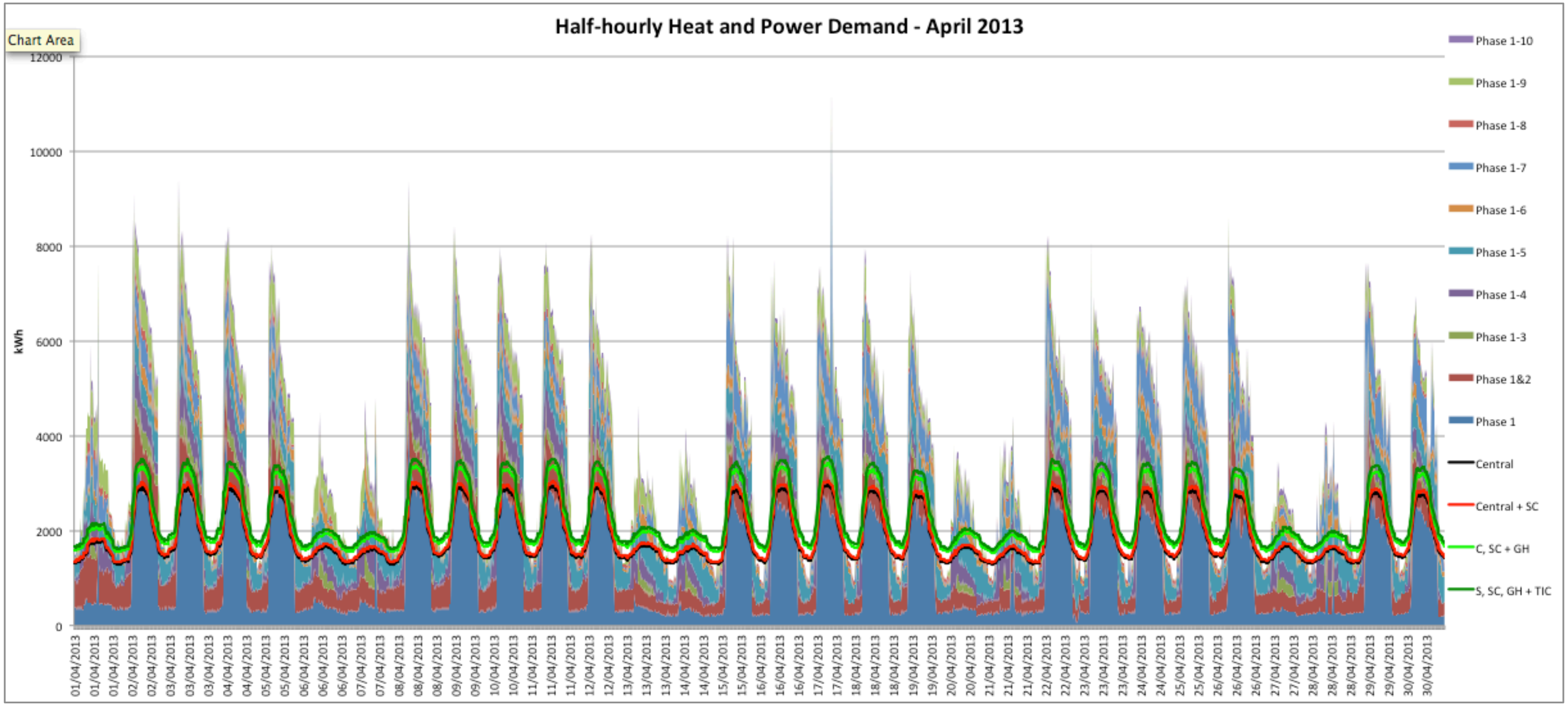


Figure 9:18 – Half-hourly Demand Profile - April

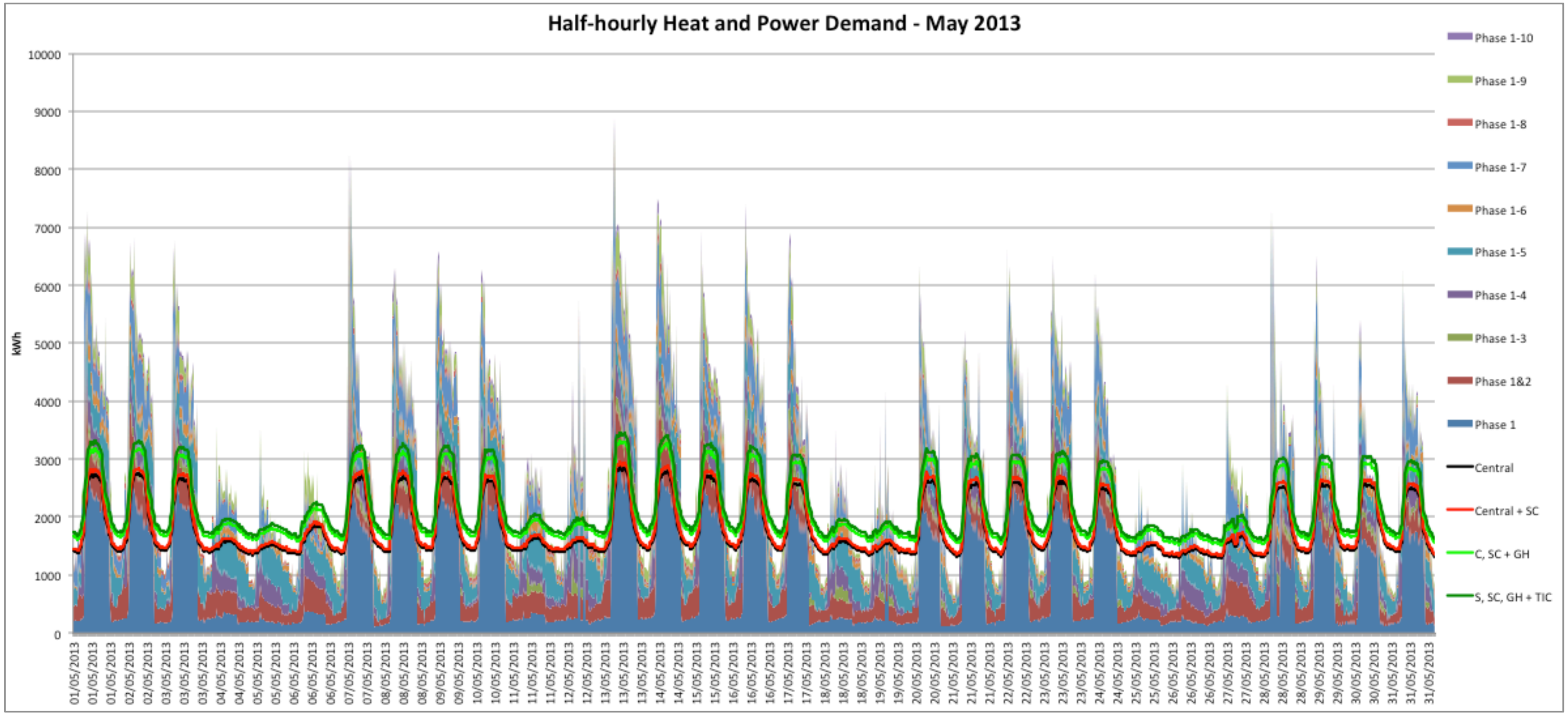


Figure 9:19 – Half-hourly Demand Profile - May

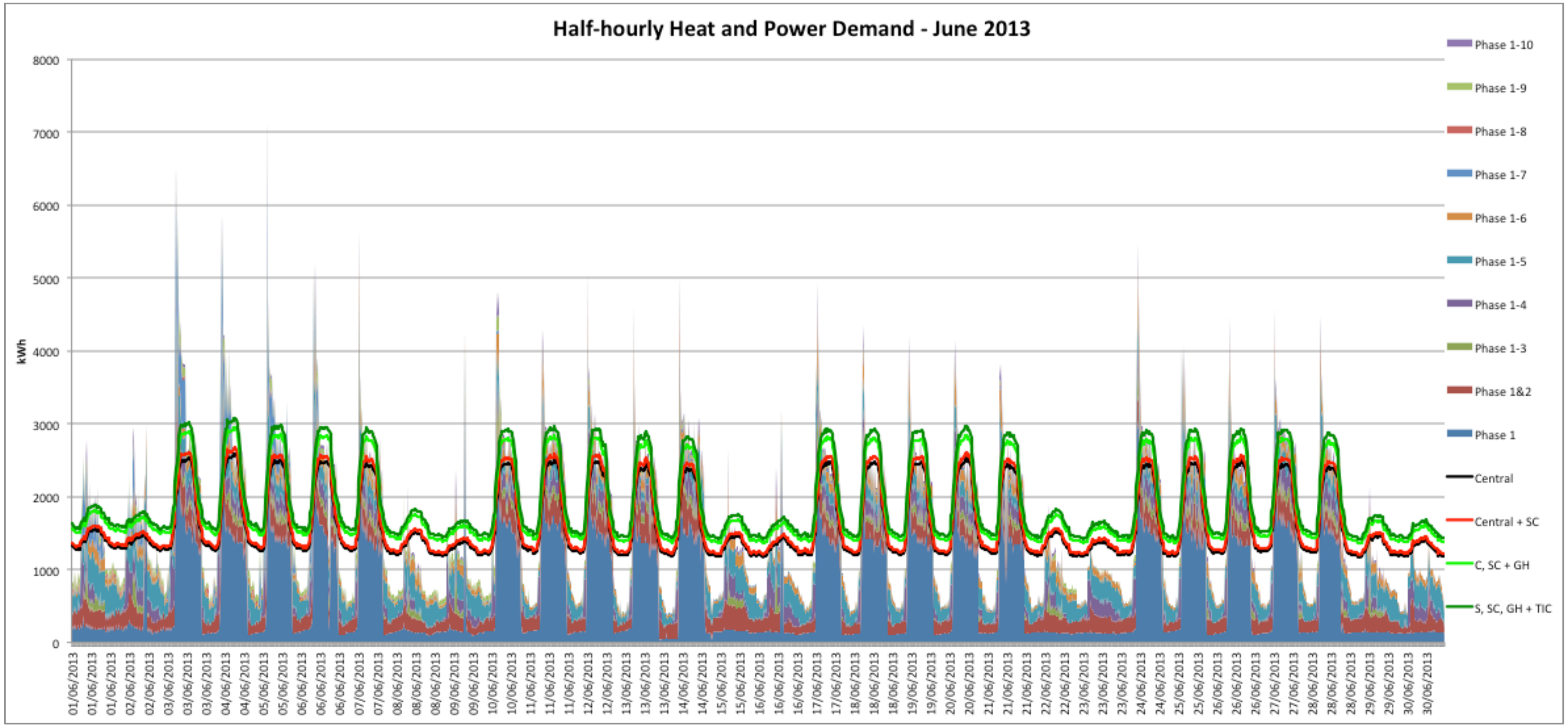


Figure 9:20 – Half-hourly Demand Profile - June

Appendix 22 – Half-hourly Analysis: Full HPR Summary

HEAT TO POWER RATIO 1 (Central)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
3.2765	3.6657	4.0020	4.4180	4.7690	5.0491	5.5521	5.6701	6.0555	6.1077
0.0000	0.0000	0.0000	0.0789	0.0789	0.0789	0.0789	0.0789	0.0789	0.0789
0.4936	0.7214	0.8245	0.9914	1.2586	1.3438	1.4576	1.4965	1.6341	1.6521
HEAT TO POWER RATIO 2 (Central & Sports Centre)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
3.1762	3.5535	3.8795	4.2828	4.6231	4.8945	5.3822	5.4966	5.8702	5.9208
0.0000	0.0000	0.0000	0.0765	0.0765	0.0765	0.0765	0.0765	0.0765	0.0765
0.4785	0.6994	0.7992	0.9610	1.2201	1.3026	1.4130	1.4507	1.5841	1.6015
HEAT TO POWER RATIO 3 (Central, Sports Centre & Graham Hills)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
2.7823	**3.1129**	**3.3984**	3.7526	4.0497	4.2876	4.6709	4.7701	5.0943	5.1383
0.0000	**0.0000**	**0.0000**	0.0646	0.0646	0.0646	0.0646	0.0646	0.0646	0.0646
0.4235	**0.6171**	**0.7048**	0.8468	1.0729	1.1454	1.2430	1.2761	1.3931	1.4085
HEAT TO POWER RATIO 4 (Central, Sports Centre, Graham Hills & TIC Building)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
2.6717	**2.9891**	**3.2632**	3.6033	3.8887	4.1170	4.4867	4.5821	4.8935	4.9357
0.0000	**0.0000**	**0.0000**	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621
0.4065	**0.5924**	**0.6766**	0.8129	1.0301	1.0997	1.1933	1.2251	1.3374	1.3522

Table 9:9

Appendix 23 – Half-hourly Analysis: Averaged HPR for 21st December 2012

Table 9:16 – Averaged Half-hourly HPR for 21st December 2012

	Half-hourly HtP Ratios (Central, SC & GH Sub) - 21st Dec									
Time	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
00:30	0.203	0.438	0.438	0.496	0.713	0.741	0.766	0.766	0.820	0.820
01:00	0.202	0.418	0.418	0.438	0.646	0.674	0.698	0.698	0.755	0.757
01:30	0.207	0.436	0.436	0.475	0.666	0.700	0.724	0.859	0.914	0.915
02:00	0.199	0.415	0.415	0.456	0.642	0.669	0.697	0.756	0.812	0.813
02:30	0.205	0.429	0.429	0.468	0.659	0.687	0.711	0.763	0.819	0.819
03:00	0.208	0.437	0.437	0.477	0.651	0.686	0.708	0.758	0.814	0.815
03:30	0.210	0.431	0.431	0.471	0.647	0.668	0.692	0.747	1.124	1.125
04:00	0.206	0.439	0.439	0.479	0.655	0.689	0.717	0.767	1.158	1.159
04:30	0.202	0.425	0.425	0.445	0.627	0.655	0.677	0.792	1.186	1.187
05:00	0.209	0.438	0.438	0.478	0.641	0.669	0.693	0.760	1.149	1.151
05:30	0.225	0.484	0.484	0.540	0.722	0.776	0.798	0.868	1.253	1.254
06:00	0.231	0.475	0.475	0.522	0.715	0.748	0.814	0.886	1.279	1.286
06:30	0.445	0.858	0.858	1.290	1.477	1.760	2.325	2.391	2.746	2.827
07:00	1.641	2.007	2.007	2.390	2.673	2.842	3.306	3.371	3.713	3.786
07:30	1.502	1.793	1.793	1.989	2.236	2.374	2.711	2.812	3.107	3.151
08:00	1.483	1.728	1.728	1.871	2.054	2.138	2.426	2.507	2.750	2.783
08:30	1.185	1.429	1.805	1.967	2.186	2.329	2.622	2.702	2.922	2.955
09:00	1.076	1.316	1.744	1.875	2.062	2.178	2.473	2.544	2.778	2.808
09:30	0.962	1.174	1.494	1.594	1.763	1.897	2.164	2.228	2.424	2.450
10:00	0.931	1.132	1.364	1.503	1.679	1.795	2.057	2.113	2.304	2.330
10:30	0.908	1.106	1.304	1.421	1.599	1.709	1.946	2.009	2.205	2.229
11:00	0.889	1.095	1.251	1.363	1.531	1.673	1.936	1.996	2.198	2.223
11:30	0.941	1.138	1.280	1.426	1.600	1.704	1.969	2.024	2.229	2.254
12:00	0.866	1.066	1.208	1.330	1.504	1.626	1.897	1.950	2.132	2.156
12:30	0.928	1.133	1.296	1.321	1.517	1.658	1.944	2.001	2.202	2.228
13:00	0.954	1.161	1.312	1.335	1.520	1.623	1.905	1.963	2.169	2.194
13:30	0.983	1.205	1.361	1.384	1.572	1.666	1.961	2.013	2.213	2.240
14:00	0.890	1.117	1.280	1.304	1.513	1.569	1.866	1.926	2.135	2.162
14:30	0.634	0.858	1.025	1.050	1.253	1.294	1.597	1.659	1.873	1.901
15:00	0.046	0.282	0.457	0.484	0.703	0.746	1.069	1.128	1.367	1.396
15:30	0.049	0.266	0.467	0.495	0.714	0.763	1.030	1.096	1.342	1.373
16:00	0.049	0.288	0.452	0.480	0.712	0.757	1.075	1.145	1.383	1.413
16:30	0.051	0.300	0.489	0.533	0.762	0.808	1.127	1.192	1.449	1.480
17:00	0.052	0.323	0.497	0.527	0.781	0.834	1.158	1.231	1.483	1.519
17:30	0.056	0.323	0.507	0.539	0.817	0.867	0.976	1.016	1.281	1.316
18:00	0.056	0.323	0.537	0.579	0.842	0.894	0.968	1.003	1.257	1.292
18:30	0.064	0.335	0.516	0.534	0.844	0.901	0.924	0.966	1.239	1.278
19:00	0.067	0.327	0.458	0.494	0.806	0.869	0.889	0.931	1.188	1.228
19:30	0.065	0.297	0.458	0.495	0.810	0.875	0.899	0.942	1.225	1.265
20:00	0.064	0.303	0.494	0.532	0.847	0.906	0.925	0.966	1.253	1.294
20:30	0.067	0.314	0.452	0.524	0.843	0.904	0.926	0.926	1.198	1.239
21:00	0.071	0.307	0.480	0.519	0.847	0.917	0.942	0.942	1.205	1.244
21:30	0.068	0.271	0.476	0.516	0.867	0.931	0.955	0.955	0.961	0.962
22:00	0.073	0.257	0.257	0.277	0.645	0.719	0.741	0.741	0.746	0.748
22:30	0.076	0.282	0.282	0.324	0.668	0.735	0.758	0.758	0.764	0.766
23:00	0.075	0.255	0.255	0.298	0.651	0.725	0.751	0.753	0.759	0.760
23:30	0.078	0.277	0.277	0.330	0.569	0.615	0.639	0.639	0.645	0.646
00:00	0.225	0.480	0.480	0.524	0.742	0.773	0.805	0.805	0.869	0.869

Appendix 24 – Half-hourly Analysis: HPR, Summary of Daily Averages

HEAT TO POWER RATIO 1 (Central)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	Max/Min/Mean
1.0954	1.4332	1.6443	1.8460	2.1761	2.2985	2.5901	2.6734	2.8244	2.8565	1.0954
0.1010	0.2433	0.2464	0.3212	0.5364	0.6081	0.6154	0.6155	0.6451	0.6562	0.6562
0.4936	0.7214	0.8245	0.9914	1.2586	1.3438	1.4576	1.4965	1.6341	1.6521	1.2586
HEAT TO POWER RATIO 2 (Central & Sports Centre)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	
1.0619	1.3893	1.5940	1.7895	2.1095	2.2282	2.5108	2.5916	2.7380	2.7691	1.0619
0.0979	0.2359	0.2389	0.3114	0.5200	0.5895	0.5966	0.5967	0.6253	0.6362	0.6362
0.4785	0.6994	0.7992	0.9610	1.2201	1.3026	1.4130	1.4507	1.5841	1.6015	1.2201
HEAT TO POWER RATIO 3 (Central, Sports Centre & Graham Hills)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	
0.9159	1.1970	1.3731	1.5411	1.8148	1.9169	2.1607	2.2304	2.3559	2.3827	0.9159
0.0871	0.2081	0.2128	0.2750	0.4592	0.5207	0.5270	0.5270	0.5573	0.5670	0.5670
0.4235	0.6171	0.7048	0.8468	1.0729	1.1454	1.2430	1.2761	1.3931	1.4085	1.0729
HEAT TO POWER RATIO 4 (Central, Sports Centre, Graham Hills & TIC Building)										
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10	
0.8800	1.1501	1.3193	1.4808	1.7439	1.8419	2.0762	2.1431	2.2638	2.2895	0.8800
0.0836	0.1998	0.2042	0.2639	0.4408	0.4998	0.5058	0.5059	0.5348	0.5440	0.5440
0.4065	0.5924	0.6766	0.8129	1.0301	1.0997	1.1933	1.2251	1.3374	1.3522	1.0301

Table 9:17 - Half-hourly Analysis: Summary of Daily HPR Averages

Appendix 25 – Half-hourly Analysis: HPR, Summary of Monthly Averages

HEAT TO POWER RATIO 1 (Central)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.6217	0.8596	1.0129	1.1998	1.4779	1.5750	1.7088	1.7588	1.9571	1.9760
0.3380	0.4829	0.5137	0.6083	0.7787	0.8447	0.8722	0.8776	0.9017	0.9153
0.4821	0.7158	0.8241	0.9956	1.2675	1.3522	1.4717	1.5120	1.6542	1.6727
HEAT TO POWER RATIO 2 (Central & Sports Centre)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.6026	0.8333	0.9819	0.9819	1.1631	1.4327	1.6565	1.7050	1.8972	1.9155
0.3277	0.4681	0.4980	0.4980	0.5897	0.7549	0.8455	0.8508	0.8741	0.8873
0.4674	0.6939	0.7989	0.7989	0.9651	1.2287	1.4267	1.4657	1.6036	1.6215
HEAT TO POWER RATIO 3 (Central, Sports Centre & Graham Hills)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.5291	0.7300	0.8599	1.0179	1.2530	1.3342	1.4481	1.4906	1.6584	1.6744
0.2953	0.4208	0.4477	0.5300	0.6772	0.7344	0.7583	0.7630	0.7838	0.7957
0.4133	0.6117	0.7038	0.8495	1.0793	1.1514	1.2536	1.2879	1.4087	1.4245
HEAT TO POWER RATIO 4 (Central, Sports Centre, Graham Hills & TIC Building)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.5080	0.7009	0.8257	0.9775	1.2033	1.2813	1.3906	1.4314	1.5926	1.6080
0.2832	0.4037	0.4295	0.5084	0.6496	0.7045	0.7274	0.7319	0.7519	0.7633
0.3967	0.5872	0.6757	0.8155	1.0363	1.1055	1.2036	1.2365	1.3525	1.3677

Table 9:18 - Half-hourly Analysis: Summary of Daily HPR Averages

Appendix 26 – Waste Heat Analysis: Graphs of Waste Heat Availability

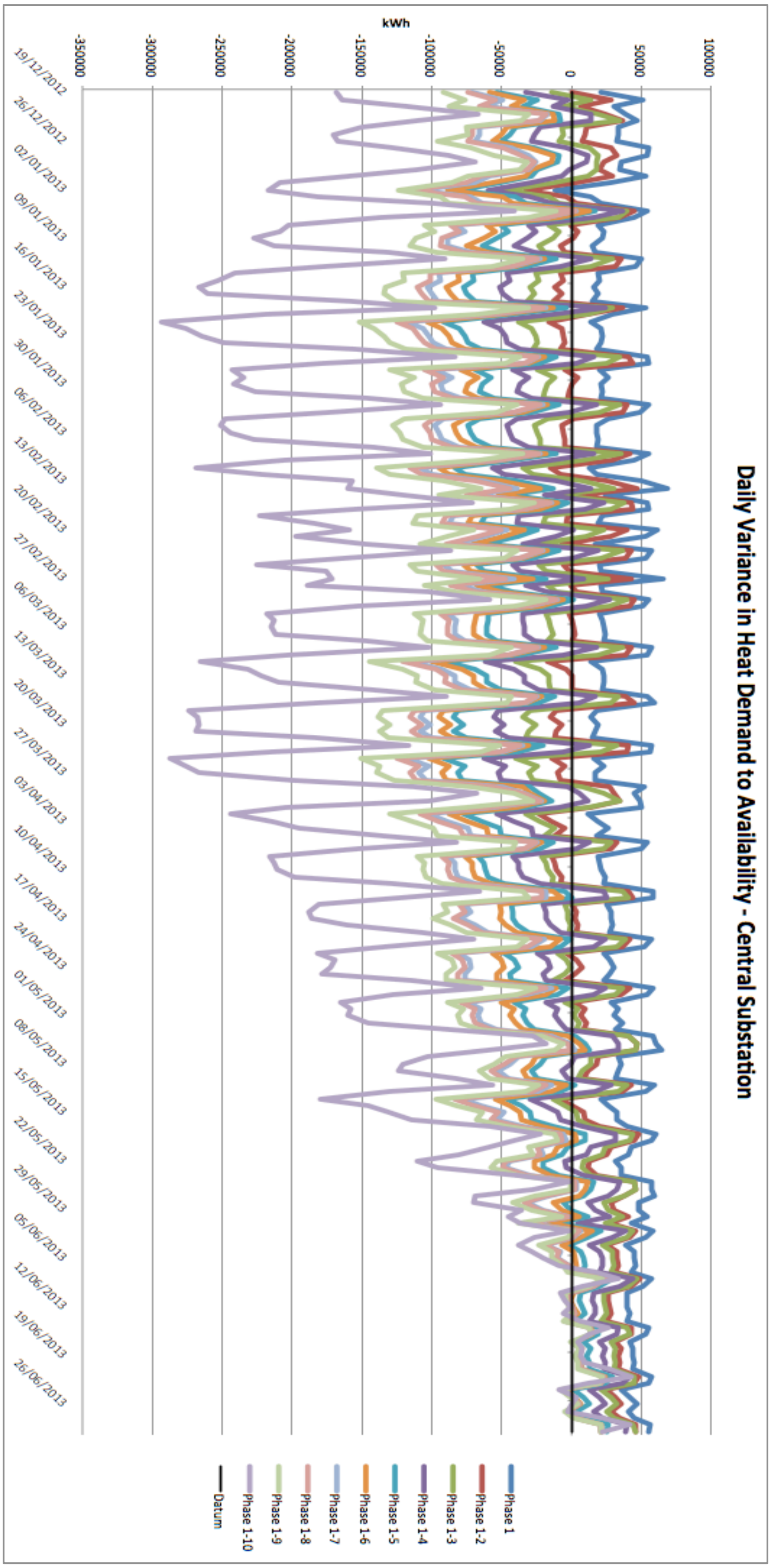


Figure 9:21 – Waste Heat Analysis: Variation in Available Heat

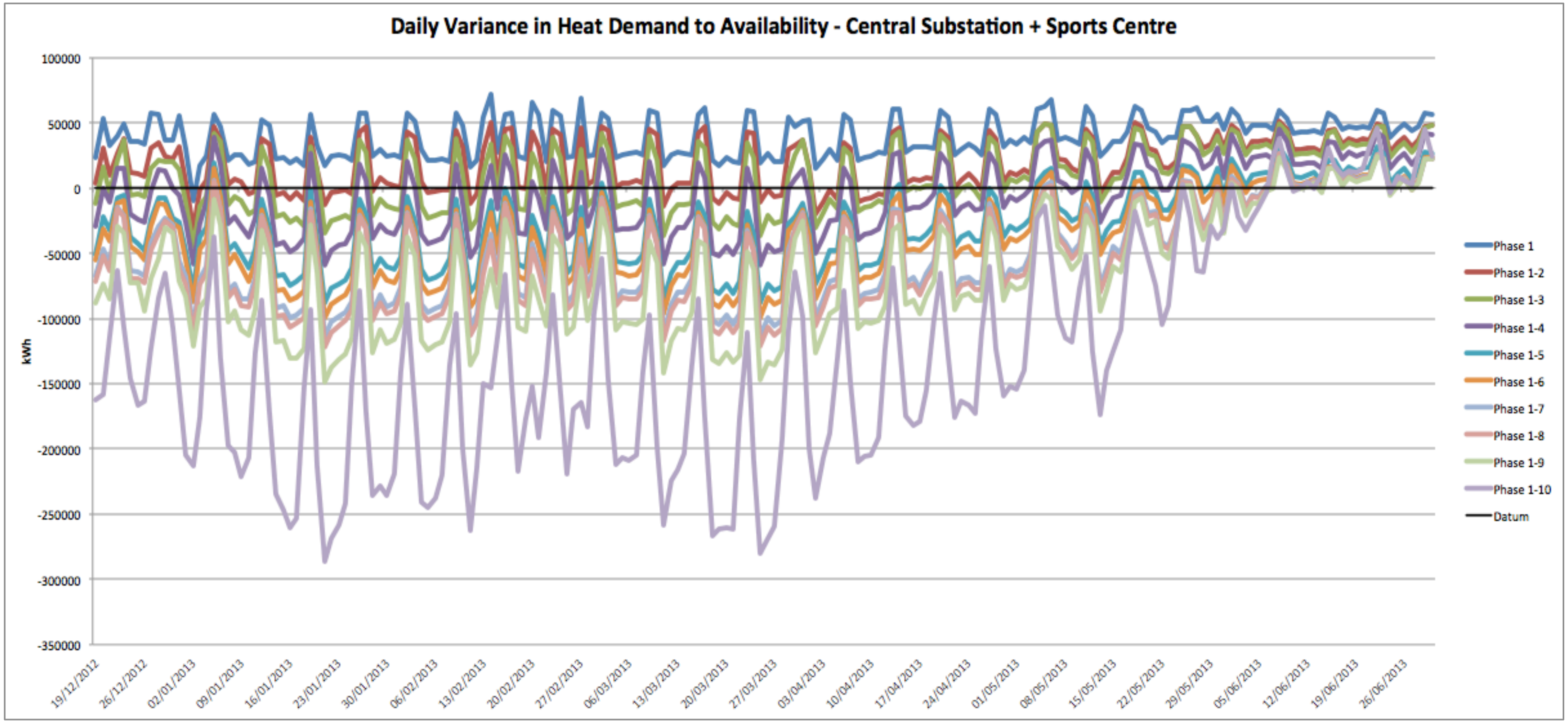


Figure 9:22 – Waste Heat Analysis: Variation in Available Heat

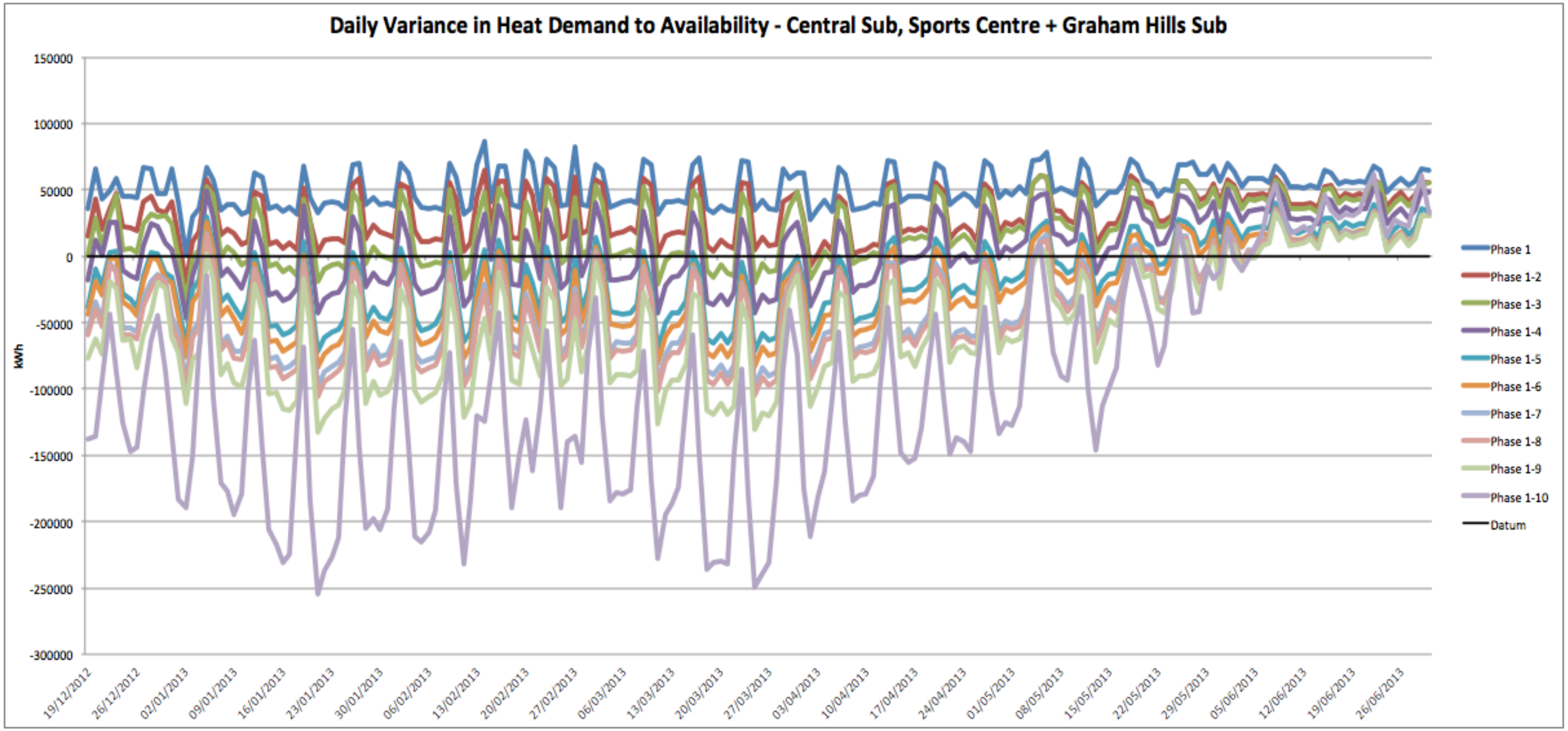


Figure 9:23 – Waste Heat Analysis: Variation in Available Heat

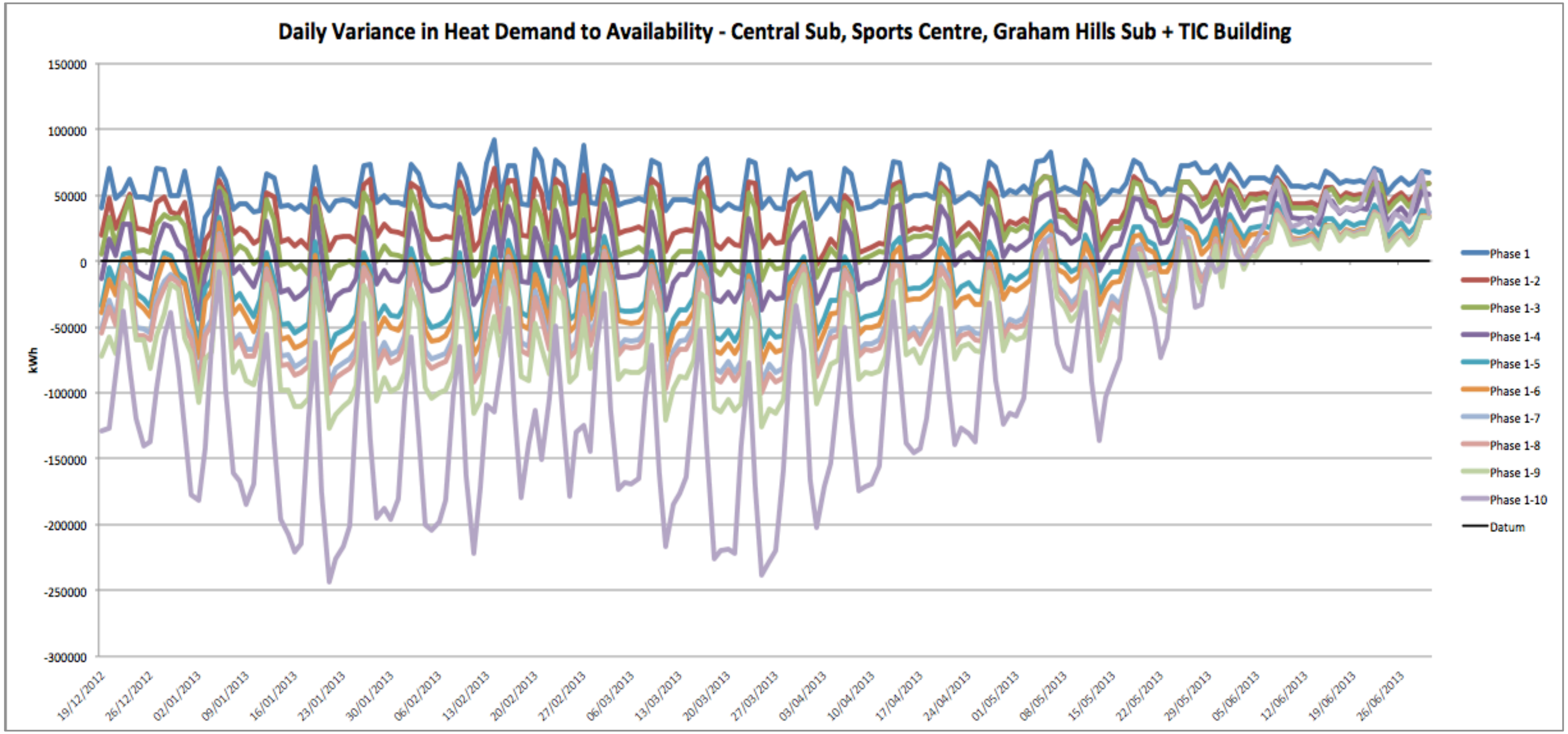


Figure 9:24 – Waste Heat Analysis: Variation in Available Heat

Appendix 27 – Waste Heat Analysis: Heat Availability Summary Table

Daily Variance In Heat Demand - Summary of Phased Available Heat

		Phase 1	Phase 1-2	Phase 1-3	Phase 1-4	Phase 1-5	Phase 1-6	Phase 1-7	Phase 1-8	Phase 1-9	Phase 1-10
Phase 1	Max	68240.08	48596.38	47150.54	43333.60	29455.35	24682.68	24227.28	24220.91	21972.95	42180.16
	Min	-11807.32	-33298.55	-47042.78	-62661.62	-91654.69	-103226.58	-117932.62	-125328.05	-152200.81	-293475.70
	Mean	36386.66	16525.37	6721.52	-7943.27	-30394.23	-38317.87	-49737.95	-53414.13	-66234.64	-131989.97
Phase 2	Max	71611.73	50621.66	49331.27	45358.88	31480.63	26707.96	26252.56	26246.19	23985.17	46131.28
	Min	-9828.25	-31319.48	-45063.71	-59086.41	-88107.88	-99766.17	-114357.41	-121867.64	-148740.40	-286492.51
	Mean	39177.70	19316.42	9512.56	-5152.22	-27603.18	-35526.82	-46946.91	-50623.09	-63443.59	-126423.11
Phase 3	Max	86490.13	65208.36	60196.87	54106.58	40228.33	35455.66	35000.26	34993.89	32263.69	61886.18
	Min	966.45	-20524.78	-34269.01	-47138.17	-72005.88	-83629.77	-98283.81	-105731.24	-132604.00	-254552.61
	Mean	51473.47	31612.18	21808.32	7143.54	-15307.42	-23231.06	-34651.15	-38327.32	-51147.83	-101890.93
Phase 4	Max	91699.43	70417.65	63566.16	57235.70	43357.45	38584.78	38129.38	38123.01	35392.81	67990.78
	Min	4024.16	-17467.07	-31211.30	-44080.46	-66625.05	-78283.34	-92782.63	-100384.81	-127257.57	-243763.40
	Mean	55785.71	35924.42	26120.56	11455.78	-10995.18	-18918.82	-30338.91	-34015.08	-46835.59	-93289.37

Table 9:24 – Waste Heat Analysis: Available Heat Summary

Appendix 28 – Cooling Analysis: EPC Calculated Cooling Loads

	Phase 1				Phase 2					
	Royal College	James Weir	Thomas Graham	Students Union	Hamnett Wing	Henry Dyer	J.A (Robertson)	SWD	Stenhouse	SBS
	9	5.5	3.46	3.03	7.10	9.09	5.94	5.66	6.76	10.44
JUL 2012	31029.90	11605.12	6352.98	1071.29	12835.51	2426.21	18212.51	955.55	1387.00	6952.87
AUG 2012	31990.08	11964.23	6716.21	1310.71	14825.60	2899.09	15672.15	1000.24	1662.55	7793.64
SEP 2012	31270.29	11695.03	5907.85	1722.87	11511.89	2267.98	15722.62	1058.62	1302.18	6785.76
OCT 2012	36409.72	13617.17	6832.71	2131.34	12560.55	2533.52	16684.20	1449.47	1642.21	8088.18
NOV 2012	37456.50	14008.66	7186.45	2129.55	13167.32	2668.11	18134.13	1500.05	1740.48	8193.67
DEC 2012	35363.00	13225.70	5394.45	1611.23	11571.65	2221.60	16091.93	1895.20	1368.96	6849.47
JAN 2013	38561.85	14422.06	6139.79	1777.55	13099.33	2470.77	17362.14	1922.52	1697.22	7211.89
FEB 2013	36884.46	13794.72	7256.33	2005.99	11655.61	2677.20	16686.04	1925.80	1841.66	7907.49
MAR 2013	40024.48	14969.08	7569.05	1823.28	10837.05	2571.71	19372.34	1798.29	1753.73	7806.18
APR 2013	36766.81	13750.72	6477.28	1556.13	14308.54	2636.28	15817.38	1618.79	1549.62	7937.78
MAY 2013	36203.77	13540.14	7082.80	1767.79	2099.96	3788.46	22314.79	1422.83	1567.86	7983.73
JUN 2013	31174.73	11659.29	6662.10	1153.57	7545.70	1365.88	9217.61	657.47	1226.49	7573.27
TOTAL	423135.60	158251.93	79578.00	20061.29	136018.72	30526.81	201287.84	17204.84	18739.97	91083.91

Table 9:10 – Cooling Analysis: Cooling Loads Calculated from EPC data

(Table 9:25 ctd.)

Phase 3	Phase 4			Phase 8		Phase 9	Phase 10
Sport Centre	Curran	Colville	John Anderson	Collins	Livingston Tower	Graham Hills	TIC Build
	19.17	1.42	6.25	13.71	3.92	3.30	0.005
6675.98	37630.67	1350.36	6152.05	13271.17	2635.49	6478.07	1673.45
6957.03	37856.30	1457.53	6342.42	14680.67	2876.93	6516.91	1743.90
6715.74	35311.93	1244.18	8881.22	14194.02	2660.19	6078.90	1683.42
7707.80	41456.71	1500.60	6923.75	22338.69	3302.29	7136.71	1932.10
7897.16	43743.44	1684.39	8984.81	27794.61	3692.29	7530.37	1979.57
7442.86	39100.78	143.14	7220.81	33920.17	3425.73	6731.14	1865.69
8136.71	42591.54	180.01	9007.38	31747.13	3898.79	7332.07	2039.61
7811.90	38449.02	161.37	8372.81	31298.59	3507.15	6618.94	1958.19
8451.05	39937.34	168.88	9784.38	30842.38	3525.41	6875.15	2118.41
7831.00	39742.38	155.89	9469.69	25141.08	3335.80	6841.59	1962.98
7729.73	53107.54	174.40	11396.44	20117.80	3939.13	9142.39	1937.60
6743.03	22547.35	90.08	6089.06	11873.34	19606.55	3881.49	1690.26
90100.00	471474.99	8310.82	98624.82	277219.65	56405.74	81163.73	22585.19

Appendix 29 – Cooling Analysis: Full HPR Results Summary

HEAT TO POWER RATIO 1 (Central)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
1.1313	2.3041	3.4976	4.6876	5.8694	7.0512	8.2587	9.5387	10.7690	11.9882
0.1539	0.3157	0.4886	0.6613	0.8336	1.0059	1.1807	1.3632	1.5432	1.7236
0.5290	1.0913	1.6576	2.2291	2.7968	3.3644	3.9474	4.5747	5.1787	5.7798
HEAT TO POWER RATIO 2 (Central & Sports Centre)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
1.0961	2.3041	3.3867	4.5385	5.6828	6.8270	7.9954	9.2319	10.4220	11.6016
0.1492	0.3157	0.4734	0.6407	0.8076	0.9745	1.1439	1.3206	1.4949	1.6696
0.5125	1.0913	1.6053	2.1585	2.7082	3.2579	3.8220	4.4281	5.0124	5.5941
HEAT TO POWER RATIO 3 (Central, Sports Centre & Graham Hills)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.9432	1.9168	2.9060	3.8931	4.8745	5.8560	6.8555	7.9058	8.9220	9.9309
0.1289	0.2642	0.4085	0.5527	0.6967	0.8407	0.9866	1.1385	1.2887	1.4392
0.4526	0.9318	1.4145	1.9014	2.3855	2.8696	3.3654	3.8947	4.4073	4.9183
HEAT TO POWER RATIO 4 (Central, Sports Centre, Graham Hills & TIC Building)									
PHASE 1	PHASE 1 & 2	PHASE 1 - 3	PHASE 1 - 4	PHASE 1 - 5	PHASE 1 - 6	PHASE 1 - 7	PHASE 1 - 8	PHASE 1 - 9	PHASE 1 - 10
0.9058	1.8399	2.7887	3.7357	4.6774	5.6192	6.5776	7.5831	8.5572	9.5247
0.1238	0.2537	0.3922	0.5307	0.6689	0.8072	0.9473	1.0930	1.2371	1.3816
0.4341	0.8935	1.3562	1.8228	2.2870	2.7511	3.2260	3.7323	4.2231	4.7126

Table 9:26 – Summary of Cooling HPR Results

Appendix 30 – Cooling Analysis: Heat Availability Summary Table

		Daily Variance In Heat Demand - Summary of Phased Available Heat (kWh)									
		Phase 1	Phase 1-2	Phase 1-3	Phase 1-4	Phase 1-5	Phase 1-6	Phase 1-7	Phase 1-8	Phase 1-9	Phase 1-10
Stage 1	Max	66837.16	43056.55	30134.54	19099.92	8116.65	-2866.62	-13997.89	-25529.96	-36918.16	-48339.05
	Min	-13745.92	-91715.60	-193739.15	-295840.56	-397785.75	-499985.41	-602782.14	-707102.18	-810875.39	-914772.87
	Mean	32601.06	-24399.78	-80963.76	-137742.00	-194315.20	-250886.85	-308053.12	-366828.95	-425027.38	-483356.67
Stage 2	Max	70208.81	43056.55	32104.88	21070.26	10086.99	-896.28	-12027.55	-23559.62	-34947.82	-46368.72
	Min	-11766.85	-91715.60	-190213.47	-292314.89	-394260.08	-496410.20	-599206.93	-703526.96	-807300.18	-911197.66
	Mean	35392.11	-24399.78	-78172.72	-134950.96	-191524.15	-248095.81	-305262.08	-364037.90	-422236.33	-480565.63
Stage 3	Max	85087.21	56578.71	42497.78	31463.16	20479.89	9496.62	-1634.65	-13166.72	-24554.92	-35975.82
	Min	-972.15	-78017.99	-174783.57	-276884.99	-378830.18	-480775.37	-583170.87	-687453.36	-791226.58	-895124.06
	Mean	47687.87	-9312.97	-65876.96	-122655.20	-179228.39	-235800.05	-292966.32	-351742.14	-409940.57	-468269.87
Stage 4	Max	90296.51	60346.81	45542.00	34507.39	23524.12	12540.85	1409.57	-10122.50	-21510.70	-32931.59
	Min	2085.56	-74960.28	-169336.33	-271437.75	-373382.93	-475328.12	-577723.62	-681929.56	-785702.78	-889600.26
	Mean	52000.11	-5000.73	-61564.72	-118342.96	-174916.15	-231487.81	-288654.08	-347429.90	-405628.33	-463957.63

Table 9:27 – Cooling Analysis: Available Heat Summary

Appendix 31 – Cooling Analysis: Graphs of Waste Heat Availability

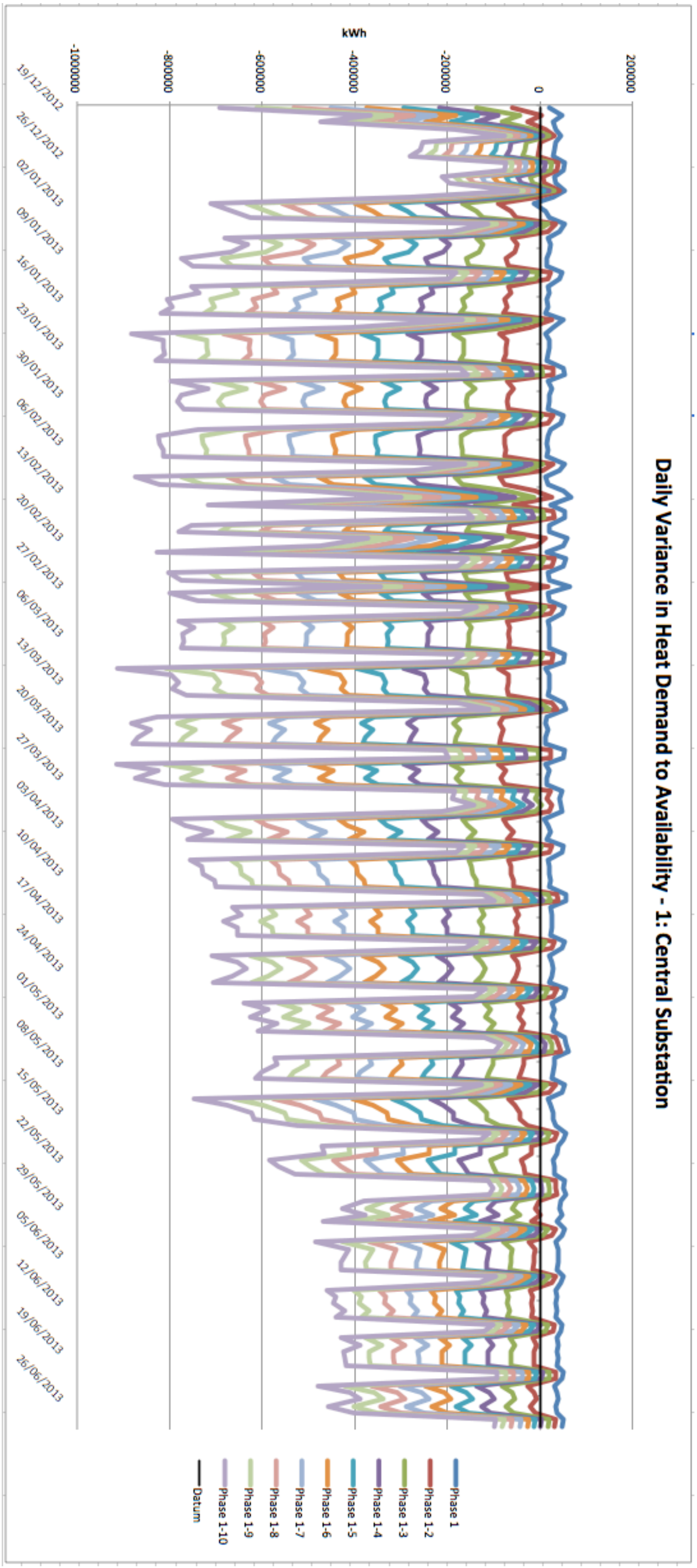


Figure 9:25 – Cooling Analysis: Daily Variance in Heat Demand

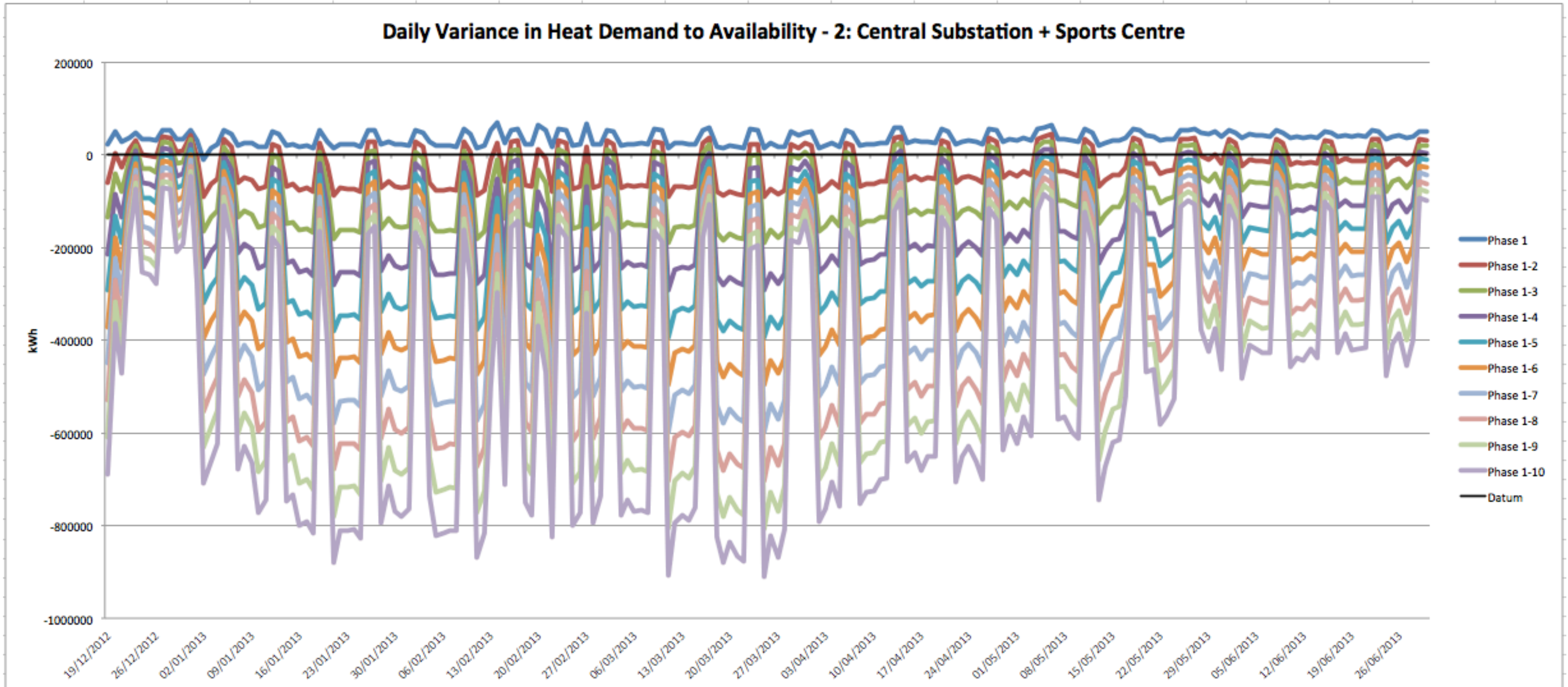


Figure 9:26 – Cooling Analysis: Daily Variance in Heat Demand

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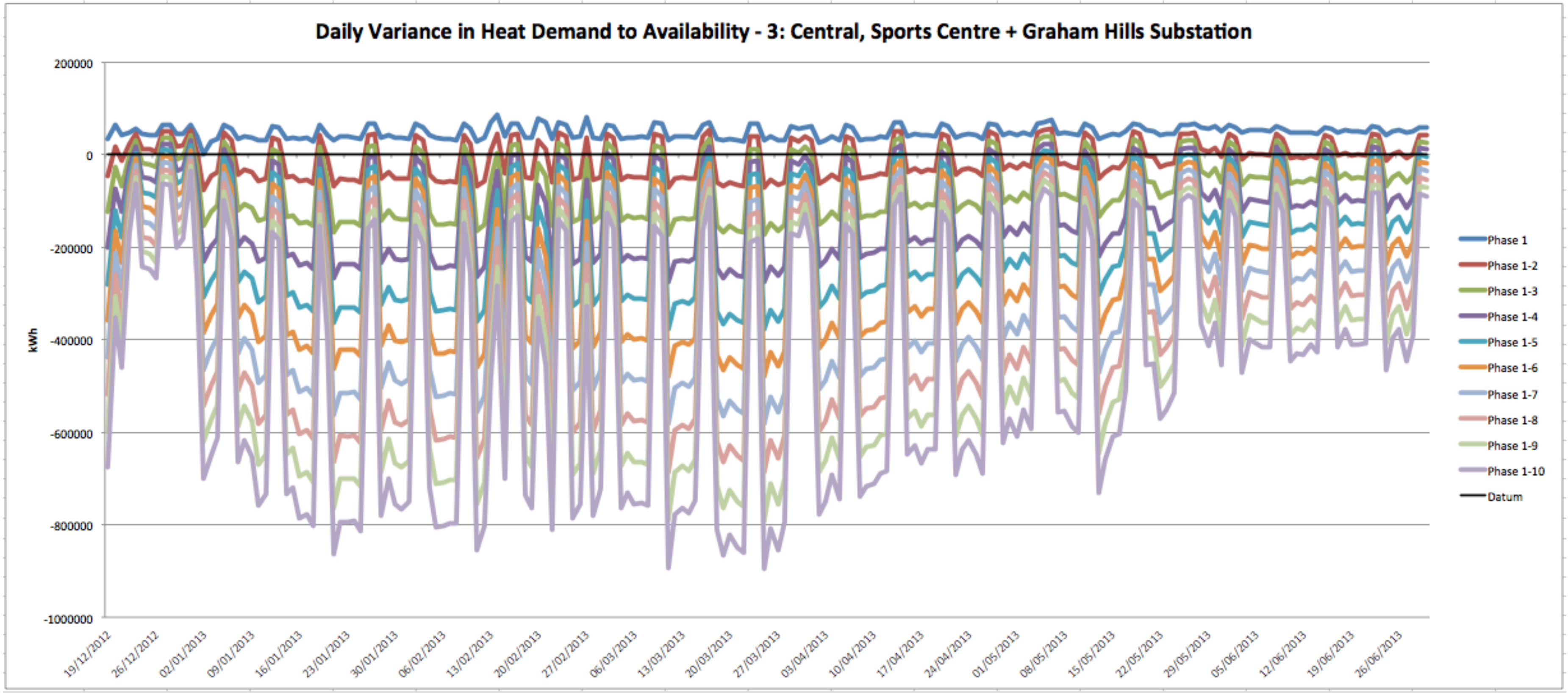

Figure 9:27 – Cooling Analysis: Daily Variance in Heat Demand

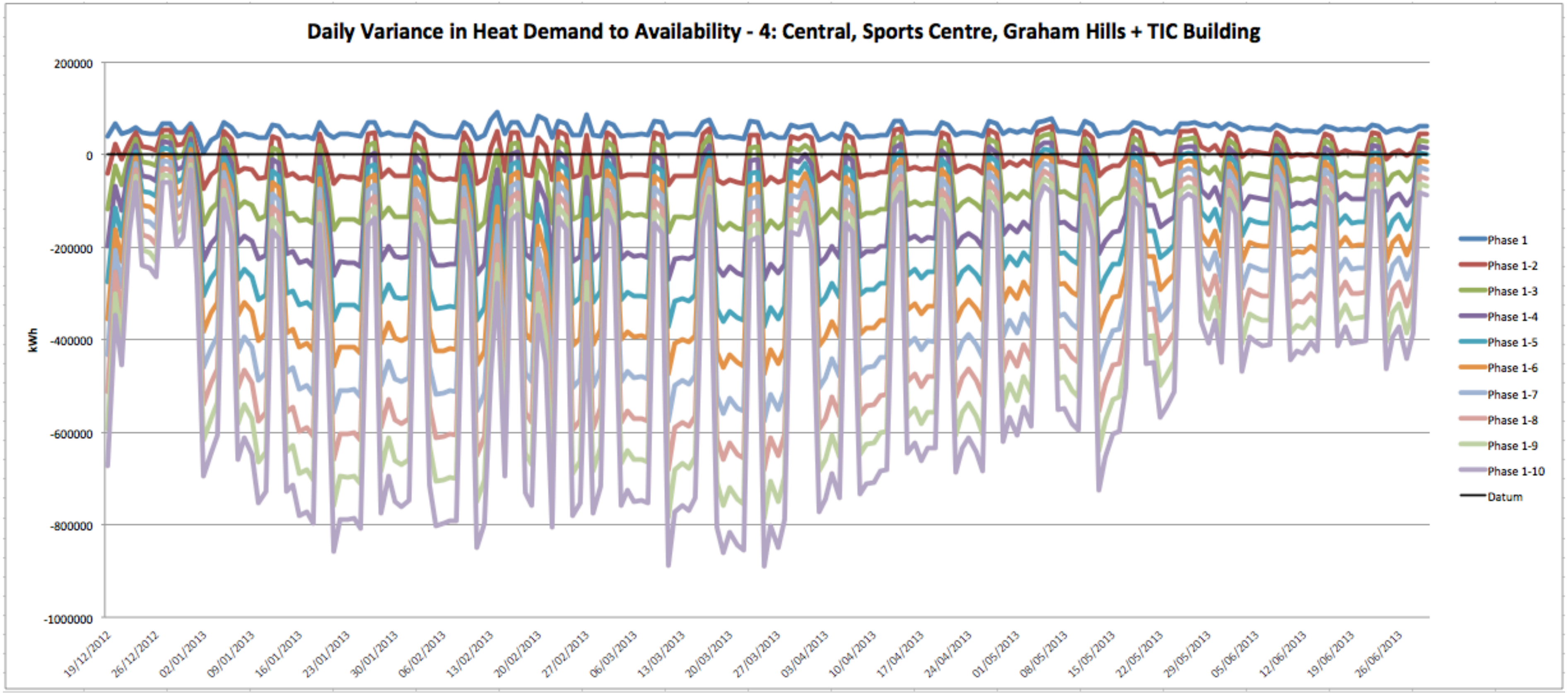

Figure 9:28 – Cooling Analysis: Daily Variance in Heat Demand

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Appendix 33 – Supplementary: Preliminary Gantt Chart

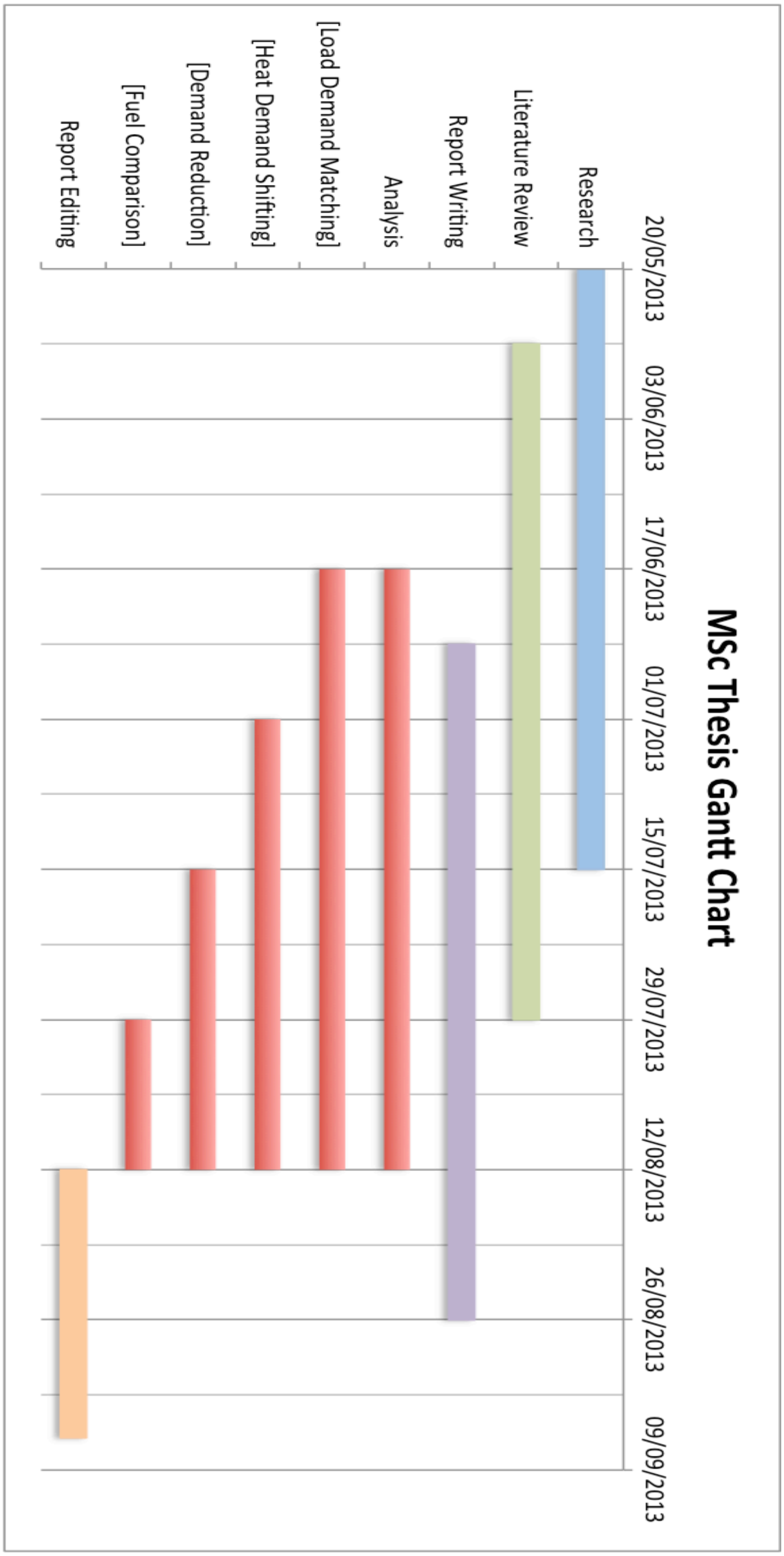

Figure 9:29 – Preliminary Gantt Chart

Appendix 34 – Supplementary: Note on the Scale of Data Used

The practicality and value of including the complete data sets used in this analysis are highly questionable; the daily profile data generated for the Sports Centre and TIC building would alone could cover multiple A4 pages. For this reason, the data sources and methods applied are clearly outlined throughout this project to ensure that the methods used in the analysis are clear and the results repeatable.

An electronic copy of each processed data set was submitted the University of Strathclyde alongside this thesis. Access to the data may subsequently be made available on request, and at the discretion of the University.