Evaluation and Optimisation of Low Energy Plant Alternatives for the National Gallery of Ireland

by

Richard Seaman

This thesis is submitted to University College Dublin in part fulfilment of the requirements for the degree

ME Energy Systems Engineering

School of Mechanical and Materials Engineering

<u>Supervisor</u>: Dr Donal Finn

September 2014

Abstract

The National Gallery of Ireland is undergoing major refurbishment works including an extensive upgrade to the mechanical and electrical systems which serve a number of the building's wings. The proposed design for these systems incorporates a number of low energy plant alternatives such as; a combined heat and power unit, a heat recovery chiller and ice banks. The existing building simulation models used for the proposed design do not account for the combined performance and interaction of the low energy plant alternatives. A specialised model is developed in TRNSYS for this purpose. Each of the low energy plant alternatives are analysed in turn to determine their optimum control philosophies for minimising energy costs and CO_2 emissions. The overall compatibility of the plant items is also analysed. The savings achieved by the combined heat and power unit were found to be the greatest. The unit provided the most savings when it maximised its power output during on-peak electrical periods and modulated its power output so that its entire heat output could be utilised during off-peak electrical periods. A number of charging and discharging options were simulated and analysed for the ice banks. It was found that a prolonged charge over the entire available charging period and chiller priority discharge control were the optimum charging and discharging options respectively. The chiller with heat recovery used in the design is capable of operating as an air source heat pump. It was found that it was only economical to operate the chiller as an air source heat pump during off-peak electrical periods due to the existing energy prices and chiller performance. However, the air source heat pump could provide CO_2 emission savings at all times. It was found that the low energy plant items had both positive and negative effects on each other. The addition of each plant item to the design provided significant energy cost or CO_2 savings. The plant items used will ultimately be funded by the taxpayer. The net present value after ten years for each possible combination of plant was calculated. The inclusion of all of the plant items resulted in the greatest net present value and therefore the greatest value for money for the taxpayer. In addition, by including each plant item, the taxpayer will have contributed to a reduction in CO_2 emissions and to the smoothing of the electrical demand on the national grid, both of which are goals of national interest. The inclusion of all three low energy plant items in the proposed design could therefore be justified.

Declaration

This thesis is the copyright of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author. Due acknowledgement must always be made of the use of any of the material contained in, or derived from, this thesis.

Acknowledgements

I have put a huge amount of work into my thesis over the past number of months and my summer seemed to whizz past in a blur. However, without the help of a number of people, I wouldn't have had the motivation or the capability of producing this thesis to the standard it is at. I would like to extend my thanks to those people now.

Firstly, I would like to thank James O'Donnell for helping me get the ball rolling back in January and for always being available to answer questions and provide guidance. I would like to thank my supervisor Donal Finn, who helped me transform my work into a presentable thesis. I also would have struggled with the software packages I used if Donal had not put me in contact with Paul McKenna and Aidan Jones, to whom I am also grateful.

I would like to thank Chris Croly of BDP for offering his guidance and expertise throughout the entire project. Without Chris and BDP's support I would not have been able to do my thesis on the NGI systems and I certainly would have struggled with some of the technical aspects of the project.

Lastly, I would like to thank my parents for both financially supporting me through my time at college and for encouraging me with their best wishes.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AHU	Air handling unit
ASHP	Air source heat pump
BDP	Building Design Partnership
CHP	Combined heat and power
CHW	Chilled water
CO_2	Carbon dioxide
COP	Coefficient of performance
DLL	Dynamic link library
EER	Energy efficiency ratio
HR	Heat recovery
HVAC	Heating, ventilation and air conditioning
IB	Ice bank
IDE	Integrated development environment
IDU	Indoor unit
LTHW	Low temperature hot water
MFR	Mass flow rate
NGI	Nation Gallery of Ireland
NPV	Net present value
ODU	Outdoor unit
PLR	Part load ratio
TER	Total efficiency ratio
TES	Thermal energy storage

1 Introduction

1.1 Context

The National Gallery of Ireland (NGI) consists of four main wings. Two of these wings are currently being refurbished. The refurbishment includes an extensive upgrade to the mechanical and electrical systems of the wings. An engineering consultancy company called BDP designed the mechanical and electrical systems for the refurbishment. BDP have included a number of low energy plant alternatives in their design such as; a combined heat and power (CHP) unit, an ice bank system and a chiller with heat recovery. This thesis evaluates and optimises the low energy plant alternatives included in BDP's mechanical and electrical design for the NGI building.

1.2 Motivation

An IES VE model of the NGI building has been built by BDP. These models are usually sufficient to design the mechanical and electrical systems for a building. Unfortunately, the model is unable to include each of the low energy technologies proposed in the design. BDP have carried out individual analyses on each of the plant alternatives to be used in the NGI. However, they are conscious that the interaction between these plant items has not been accounted for. A specialised model is therefore required that can simulate the overall system performance of the NGI building and analyse each of the low energy plant alternatives' performances.

1.3 Overall Aim

The overall aim of this thesis project is to evaluate and optimise a number of low energy plant items that have been included in BDP's mechanical and electrical system design for the refurbishment of the National Gallery of Ireland.

1.4 Specific Objectives

There are four specific objectives for this thesis project.

1. To optimise the control philosophy used for the combined heat and power unit included in BDP's mechanical and electrical system design.
2. To optimise the control philosophy used for the ice banks included in BDP's mechanical system design.
3. To optimise the use of the heat recovery chiller included in BDP's mechanical design as an air source heat pump.
4. To determine the compatibility of the low energy plant items included in BDP's mechanical and electrical system design.

1.5 Thesis Layout

This thesis contains a total of thirteen chapters. Chapter 1 introduces the context, aims and layout of the thesis.

Chapter 2 consists of the literature review carried out for the thesis. The technology behind each of the low energy plant items included in BDP's mechanical and electrical design for the NGI refurbishment are investigated and typical performances are identified. Existing modelling techniques for the low energy plant items are also described.

Chapter 3 briefly introduces the National Gallery of Ireland and the current refurbishment works taking place.

Chapter 4 describes the methodology used to evaluate and optimise the low energy plant items for the NGI building. A simplified methodology process diagram is provided. This diagram is referred to by each of the consecutive chapters to communicate to the reader what the chapter contains in relation to the methodology used.

Chapter 5 evaluates a number of available software packages for the modelling of the NGI's low energy plant items. Each software package is described in turn and evaluated under a number of headings. A summary table provides each software packages' ratings under each heading as well as an overall rating. The primary software package used in the thesis is selected based on these ratings and any additional software packages required are identified.

Chapter 6 describes how the performance and control options of each of the NGI's low energy plant items were determined. The performance equations used, performance data used and the finalised modelled performance are provided. The operation and control options available to each plant item are also described.

Chapter 7 describes the process used to determine the finalised NGI heating, cooling and electrical loads. The loads were first exported from an IES model provided by BDP. The loads were analysed against existing data when possible and manipulated as required.

Chapter 8 describes the TRNSYS model developed for the evaluation and optimisation of the NGI low energy plant items. The model is broken down into four main components; *NGI Load Data, User Input, Simulation Engine* and *Data Output*. Each of the four components is described in turn.

Chapter 9 addresses the first thesis objective of optimising the CHP unit control philosophy. Economic and CO_2 emission analyses are carried out to determine when and how the CHP unit should operate. Annual simulations are run to determine whether the CHP unit's heat or the chiller's heat should be given priority. Conclusions are drawn on the optimum CHP control philosophies from the economic and CO_2 analyses and an analysis of the simulation results.

Chapter 10 addresses the second thesis objective of determining the optimum ice bank control philosophy. The available ice bank charging and discharging control options are described in more detail than Chapter 6. Simulations are run to determine the optimum charging and discharging control options and conclusions are drawn from an analysis of the simulation results.

Chapter 11 addresses the third thesis objective of determining when the chiller should operate as an air source heat pump. The number of hours that the chiller can operate as an ASHP is determined for the finalised NGI loads. An analysis is carried out to determine if the ASHP or boiler should be used to provide the NGI's heating load. Simulations are run to confirm the analysis findings and conclusions are drawn.

Chapter 12 addresses the fourth and final thesis objective of determining the compatibility of the NGI's low energy plant items. The low energy plant alternatives are simulated individually, in combinations of two and finally altogether. The simulation results are analysed to determine if the combination of plant items achieve the same annual cost and CO_2 savings as the sum of those achieved by the individual use of the plant items. A conclusion is then made on the compatibility of the low energy plant alternatives.

Chapter 13 concludes the thesis. The conclusions drawn for each of the thesis objectives are reiterated and a final conclusion is made. Suggestions for future work are also provided.

2 Literature Review

This literature review explores the three low energy plant alternatives to be used in the NGI; the CHP unit, the chiller with heat recovery and the ice banks. The technology behind each plant item is investigated and good practice targets are identified. The modelling techniques used for analysing these low energy plant alternatives are also investigated.

2.1 Combined Heat and Power Unit

2.1.1 Overview

Combined heat and power is the name given to energy systems that produce both electricity and heat through a single process. In conventional buildings without CHP, the electricity and heating demands are provided by separate processes.

Heating is usually provided on site in buildings whereas electricity must be imported. Power stations provide buildings with the electricity they need via a utility grid. Generation of electricity produces heat. Power stations reject approximately 50% to 60% of the energy available to the atmosphere as *waste* heat as there are no heating loads available in the proximity of the power plant (Woods, 2013). Further losses are also incurred by transmitting the electricity from the power plant to the building.

CHP aims to reduce or eliminate these losses by generating both heat and electricity where it is required. The use of CHP to generate power and heat simultaneously on site in a building leads to savings in primary energy use. The average primary energy saving from CHP in the UK in 2007 was approximately 18%, but savings of approximately 28% are more typical for small packaged CHP schemes (The Carbon Trust, 2010).

Figure 2-1 highlights the energy savings from CHP compared to conventional sources of heat and power such as boilers and grid supplied electricity. Figure 2-1 may be interpreted as follows:

- If 100 units of fuel are used by the CHP, 35 units of electricity and 45 units of heat would be produced, with losses of 20 units.
- For a boiler of 80% efficiency to provide the same heating would require 56 units, with losses of 11 units.
- For the grid at 40% efficiency to provide the electricity would require 88 units, with losses of 53 units
- The potential savings are the difference in total energy used and are therefore approximately 30%. (1- 100/144 = 0.3)

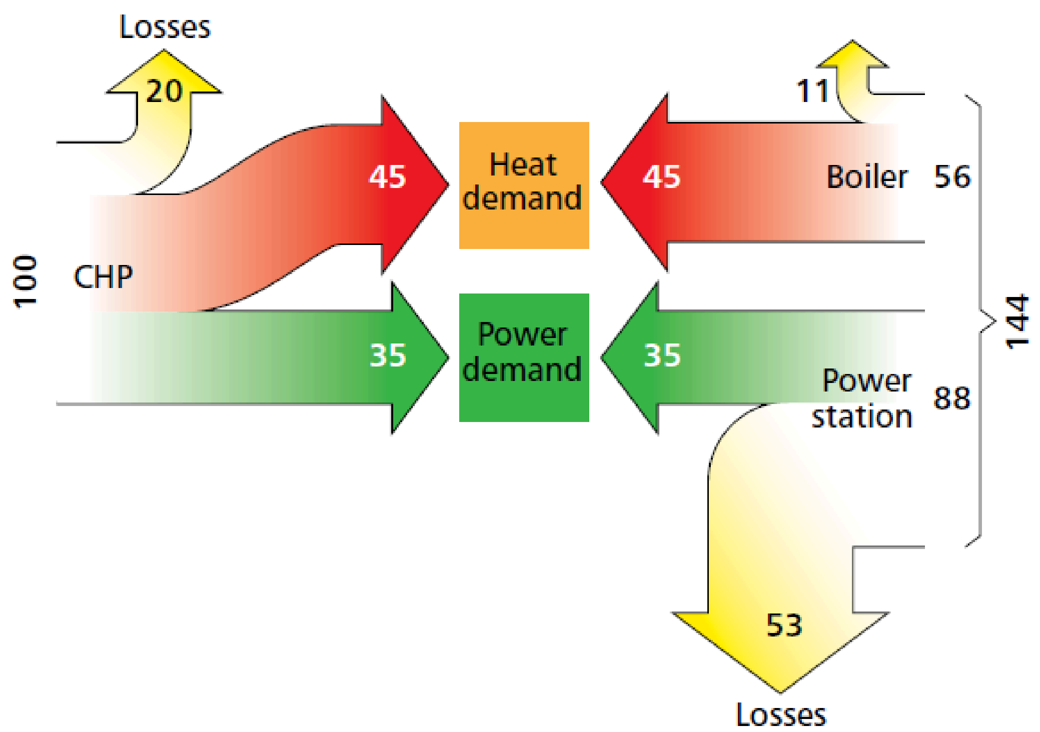


Figure 2-1: The potential energy savings of CHP compared to conventional methods shown in units of energy (Woods, 2013)

2.1.2 CHP Unit Efficiencies

CHP utilizes approximately 65-85% of the fuel used either as electricity or heat. The amount of electrical energy generated per unit of fuel used is known as the electrical efficiency. The amount of useful heat energy generated per unit of fuel used is known as the thermal efficiency. The total efficiency of the CHP is the sum of the electrical and thermal efficiencies. A well operated modern CHP unit should operate at around 35% electrical efficiency and 45% thermal efficiency (Dwyer, 2011).

2.1.3 Benefits of CHP Units

CHP is often the single biggest measure in reducing a building's energy costs and CO_2 emissions (Jones & Day, 2009). Lower operating costs are achieved with CHP as the energy consumed on site changes. More gas is purchased and used to provide both electricity and heat from the CHP unit. Less electricity is purchased as the CHP unit generates the electricity on site.

CHP reduces net CO_2 emissions. The CO_2 emissions on site actually increase as more fuel is consumed but this is offset by the electricity generated by the CHP displacing electricity that would be generated at power plants. The net reduction in CO_2 emission is therefore dependent on the CO_2 emission factors of the fuel used for the CHP and the electricity displaced by the CHP. (Woods, 2013)

In addition to reducing energy costs and CO_2 emissions, CHP can provide emergency power capability and improve power quality. It can also reduce the burden on the gird during peak demand and help avoid penalty payments for exceeding the maximum import capacity (MIC) of the building. (The Carbon Trust, 2010)

The operating cost benefit of CHP, i.e. the difference between the cost of heat and power generation by CHP and conventional methods, depends on a number of factors. Firstly, it depends on the efficiency of the CHP unit. Ideally, the CHP unit should operate at full load for the majority of the year as the electrical efficiency of the CHP unit reduces at part load. To significantly improve the operating cost benefit of CHP, the CHP unit should have an electrical generation efficiency similar to that of the grid (Zogg, et al., 2005).

The operating cost benefit of CHP also greatly depends on the energy tariffs present. CHP achieves the greatest savings when the electricity price is relatively high compared to the fuel price. Savings will be reduced when there are relatively low electricity prices and high fuel prices. Therefore the savings may be significantly reduced at night time when the electricity price is relatively low, particularly if the CHP must operate at part load due to decreased heating or electrical demands. However, it still may be economical to operate the CHP overnight if there are sufficient heating and electrical loads present (Woods, 2013).

2.1.4 CHP Unit Sizing

In order to size a CHP unit, it is necessary to know the hourly heating and electricity load profiles of the building. Averaged daily or monthly data is not sufficient as it is unclear whether the heating and electrical loads occur simultaneously. If averaged daily or monthly data is used, it may lead to optimistic results with respect to the CHP operating hours and economic return.

To achieve the full benefit of a CHP unit, it should operate as many hours a year as possible. A minimum operating time of 12 hours a day is recommended to achieve financial success and payback periods of five years or less (CIBSE, 2013). The CHP unit is usually sized to meet the base heating load, with the remainder of the heating load provided by boilers. However, the most cost effective solution may be to size the CHP at a greater capacity than the heating base load with some CHP modulating capacity and/or heat dumping during periods of low heat demand, such as during the summer months. Care must be taken not to oversize the CHP too much as it will either have to operate at part load for a higher proportion of the year or dump more heat, resulting in a loss in efficiency. Figure 2-2 shows how a CHP unit may be sized according to the base heating load. (Cheshire, 2012)

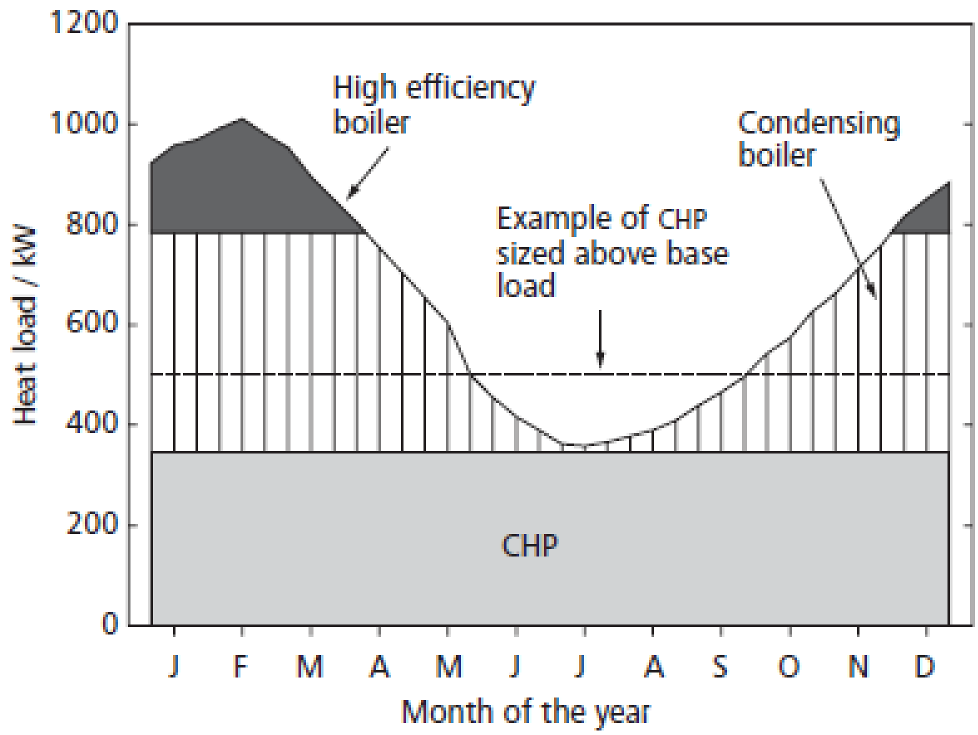


Figure 2-2: Sizing CHP for base heating loads and combining with boiler plant (Cheshire, 2012)

Alternatively, the CHP unit may be sized according to the base electrical load. If the CHP unit is sized at a greater electrical capacity than the electrical base load, it will have to modulate its output or export its excess electricity to the grid. If the CHP unit modulates its output, its electrical efficiency drops. Depending on the agreement with the electricity suppliers, it may or may not be possible to sell the excess electricity to the grid. Even if it is possible, it is generally not done as the export prices are typically 30-50% lower than import prices (Woods, 2013).

Careful consideration and a detailed analysis are therefore required to correctly size a CHP unit to achieve maximum energy, CO_2 and cost savings.

2.2 Chiller with Heat Recovery

2.2.1 Overview

In the context of building services, heat recovery can be defined as: *"the collection and re-use of heat arising from a process that would otherwise be lost."* (The Carbon Trust, 2011). A heat recovery chiller makes use of heat that would otherwise be dumped to the ambient.

A chiller is a form of heat pump that is used to provide cooling in a building. Conventional chillers transfer heat from internal evaporators to external condensers. The heat that is transferred to the external condenser is dumped to ambient. Conventional chillers do not contribute to the heating of the building. The heating must be provided by other systems, such as a boiler.

The logic of heat recovery chillers is to use one system to transfer heat within a building from where it's not needed to where it is needed. A heat recovery chiller takes heat from a cooling fluid and transfers it to a heating fluid, providing both cooling and heating from the same process. This makes more sense than providing heat from one system, such as boilers, while simultaneously dumping heat from another system, such as a conventional chiller. (Rishel & Kincald, 2007)

There must be a simultaneous demand for heating and cooling in a building so that the heat recovered by a chiller can be utilised. It is suggested by Byrne et al. that the heating and cooling loads of buildings are becoming more balanced. More stringent building thermal regulations result in less heating being required while more electrical equipment results in more cooling being required (Byrne, et al., 2011).

Figure 2-3 shows the heating and cooling loads of a building provided by; (A) a conventional chiller and boiler and (B) a heat recovery chiller and boiler. In (A), the entire heating load is provided by the boiler and the heat extracted from the cooling fluid is dumped to ambient via an air cooled condenser. In (B), the heat extracted from the cooling fluid contributes to the heating load and the remainder of the heating load is provided by the boiler. It may also be necessary to include an air cooled condenser in (B) if too much heat is recovered by the chiller.

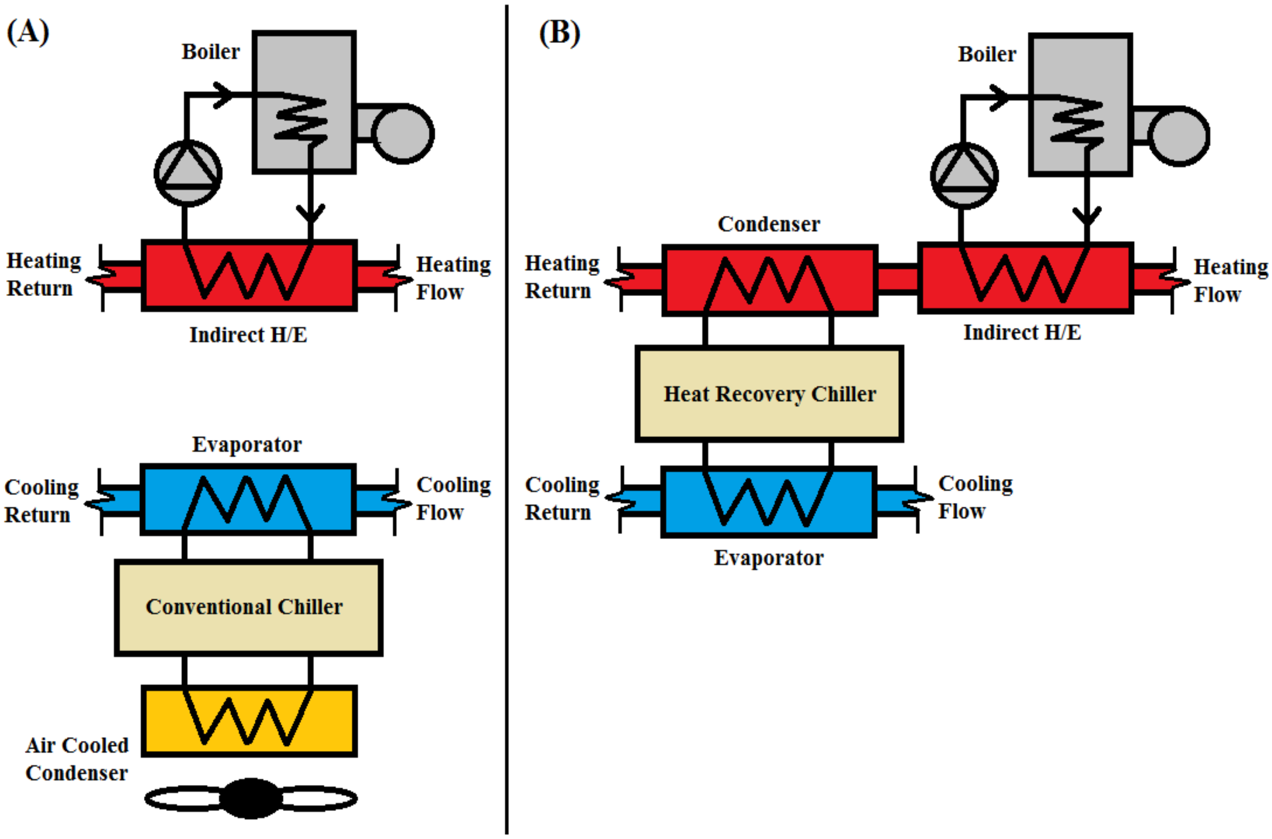


Figure 2-3: Comparison between (A) conventional chiller operation and (B) heat recovery chiller operation

2.2.2 Chiller Efficiencies

There are a number of terms used to refer to a chiller's efficiency. If the chiller provides cooling only, its efficiency is usually referred to as its energy efficiency ratio (EER). The EER is defined as the ratio of cooling provided by the chiller to work done by the chiller. If the chiller provides heating only, its efficiency is usually referred to as its coefficient of performance (COP). The COP is defined as the ratio of heating provided by the chiller to work done by the chiller. If the chiller provides both cooling and heating simultaneously, its efficiency is usually referred to as its total energy efficiency (TER), although COP is also used. In this case, the TER or COP is defined as the ratio of the sum of the heating and cooling provided by the chiller to the work done by the chiller.

The temperature *lift* required i.e. the difference between the evaporating and condensing temperatures, is possibly the most important factor affecting energy efficiency. Each one degree kelvin increase in temperature lift results in a 2%-4% increase in energy consumption (Cheshire, 2012).

The evaporating temperature depends on the chilled water setpoint temperature for both the conventional and heat recovery chillers. The condensing temperature for a conventional chiller depends on the ambient air temperature whereas the condensing temperature for a heat recovery chiller depends on the hot water setpoint temperature. The ambient air temperature and hot water setpoint temperatures may be in the range of 20°C and 45°C respectively. Therefore, the temperature lift required by a heat recovery chiller is usually much higher than that required by a conventional chiller. This means that a heat recovery chiller must do more work to transfer the heat between the two fluids. However, its coefficient of performance (COP) is usually better as the work done by the chiller provides both heating and cooling instead of just cooling.

2.2.3 Operating Modes & Partial Load Conditions

A chiller with heat recovery is a form of heat pump for simultaneous heating and cooling, also known as a HPS. Depending on the heating and cooling loads present, a HPS system may operate in different modes. The operating modes are usually broken down as follows:

- *cooling only,* when there is only a cooling load present
- *heating only,* when there is only a heating load present
- *cooling main,* when more heat is recovered than can be used (i.e. when an ambient heat sink is required)
- *heating main,* when the recoverable heat is insufficient to meet the heating load (i.e. when an ambient heat source is required)

- *total recovery,* when all of the recoverable heat is used. (i.e. when no ambient heat source or sink is required)

Kang et al. performed an experimental study on the performance of a simultaneous heating and cooling multi-heat pump system under varying operating modes. The HPS used by Kang et al., shown in Figure 2-4, employs multiple indoor units (IDU) and a single outdoor unit (ODU) which serve as evaporators or condensers depending on the operating mode of the system. Simultaneous heating and cooling can be utilised when there are demands for both heating and cooling, by opening and closing valves to apportion the refrigerant to the various evaporators and condensers.

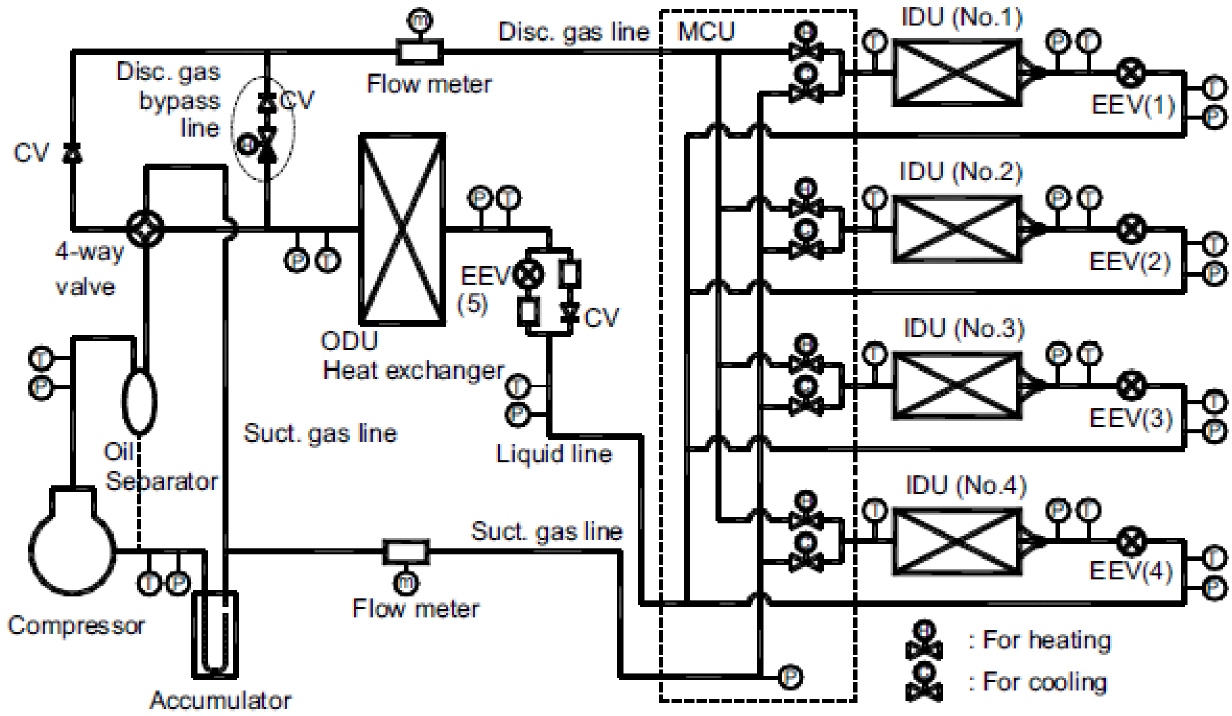


Figure 2-4: Kang et al. Experimental HPS set up (Kang, et al., 2009)

Kang et al. examined five operating modes; cooling-only, cooling-main, heating-only, heating-main and entire heat recovery. In cooling-only and heating-only modes, the only loads present were the cooling or heating load respectively. In cooling-main operating mode, the cooling load was greater than the heating load. In heating-main operating mode the heating load was greater than the cooling load. In entire heat recovery mode the heating and cooling loads were equal.

Kang et al. found that the COP of the system differed depending on the operating mode of the system. There was a 22.1% increase in COP in cooling-main mode over cooling-only mode. There was a 53.8% increase in COP in heating-main mode over heating-only mode. There was a 146.5% increase in COP in entire heat recovery mode over cooling-only mode. The increases in COP were due to heat recovery from simultaneously heating and cooling as well as reduced compressor speeds.

Joo et al. carried out a further study on the performance characteristics of this HPS at partial load ratios (PLR). The compressor speed ratio, the fan speed ratio and the electronic expansion were varied to determine the optimum method of meeting partial loads. The optimum method used to modulate the HPS differed depending on its operating mode. However, it was found that the COP of the HPS decreased as the PLR decreased, particularly at very small PLRs. (Joo, et al., 2011).

2.3 Ice Bank

2.3.1 Overview

An ice bank is a type of cool thermal energy storage. It is an indirect method of storing cooling potential for later use. An ice bank consists of a thermal storage container with some form of immersed internal heat exchanger. Figure 2-5 shows a typical ice bank. Water is used within the container as a phase change material to store the cooling potential. A chiller usually provides the cooling to be stored. A primary chilled circuit passes a glycol mix through the internal heat exchanger to freeze the water within the container. This is known as *charging* the ice bank. The same glycol mix is then passed through the ice bank at a higher temperature when the stored cooling potential is required. This is known as *discharging*. The phase change material remains in the container for both charging and discharging.

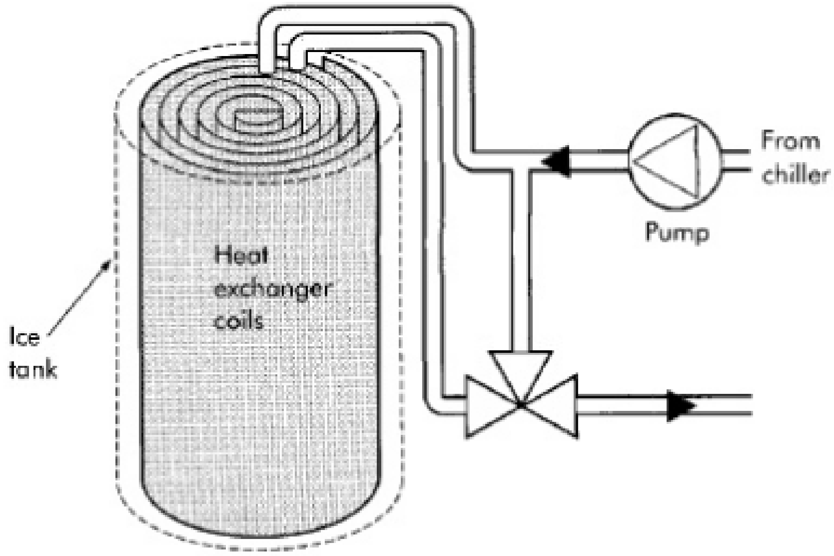


Figure 2-5: Ice Bank (Arnold, et al., 1994)

A number of phase change materials have been developed but most storage systems use water as the storage medium. Water is used due to its availability, stability, low cost, high latent heat capacity, high specific heat, safety and appropriate fusion temperature (ASHRAE, 2008).

Ice banks allow load shifting or the manipulation of energy demand profiles. Chillers are usually run overnight to charge the ice banks. Ice banks are charged overnight because the existing cooling loads are relatively small and cheaper electricity rates are available. (Warburton, et al., 2009)

A disadvantage of using ice banks is that the production and melting of ice is inherently inefficient. To charge an ice bank the chilled water produced by the chiller must be below the freezing point of water. The COP of the chiller is reduced by dropping the chilled water setpoint temperature. However, the cooler ambient air temperature at night offsets this loss in COP. The increase in chiller energy consumption may be as high as 15%-20% (Butler, 2005).

Although the chiller energy required is increased, ice banks may lead to a reduction in CO_2 emissions. In the UK, the CO_2 emissions per kWh of electricity delivered from the grid is lower overnight than during the day. More energy is used overnight when the electricity emission factor of the grid is low and less energy is used during the day when the electricity emission factor of the grid is high. The CO_2 savings achieved therefore depend on the charging and discharging times of the ice bank and the respective electricity emission factors of the grid. (Butler, 2005)

2.3.2 Ice Bank Sizing

Ice banks are not usually designed to provide the entire cooling load on a design day. If the ice banks were sized to provide the entire design day cooling load the ice banks would only fully discharge for a number of days per year. The capital cost would be significantly increased as larger ice banks or a greater quantity of ice banks would be required. This increased capital cost would not be justified as the running costs would remain mostly unchanged.

Sizing the ice banks to provide some of the design day cooling load is known as *partial storage*. Peak loads are met by discharging the ice bank and running the chiller at the same time. Partial storage reduces the maximum cooling demand to be met by the chiller. This may allow a smaller chiller to be used, reducing the capital cost required. It could also lead to a reduced peak electrical demand, which could potentially reduce maximum electrical demand charges. (Warburton, et al., 2009)

2.3.3 Discharge Control Strategies

There are three main conventional control strategies for discharging an ice bank: chiller priority, constant proportion and store priority. Chiller priority is the most widely used control strategy (Henze, et al., 2003).

With chiller priority control, the chiller provides as much of the cooling load as it can and the remainder is provided by the ice bank. The chiller turns off when the ice bank can provide the remaining cooling demand for the day. The chiller must therefore be downsized to make the ice storage system feasible.

Constant proportion control prescribes a constant fraction of the cooling load that is to be met by the ice bank during peak electrical rate hours. A load fraction of 25% is found to provide good load shifting performance without premature depletion of the ice bank for a wide variety of cases (Henze, et al., 2003).

Store priority control is similar to constant proportion control except that the load fraction is calculated daily from cooling load predictions. The load fraction is calculated such that the storage is fully depleted by the end of the next on-peak period.

Figure 2-6 compares store priority and chiller priority control strategies.

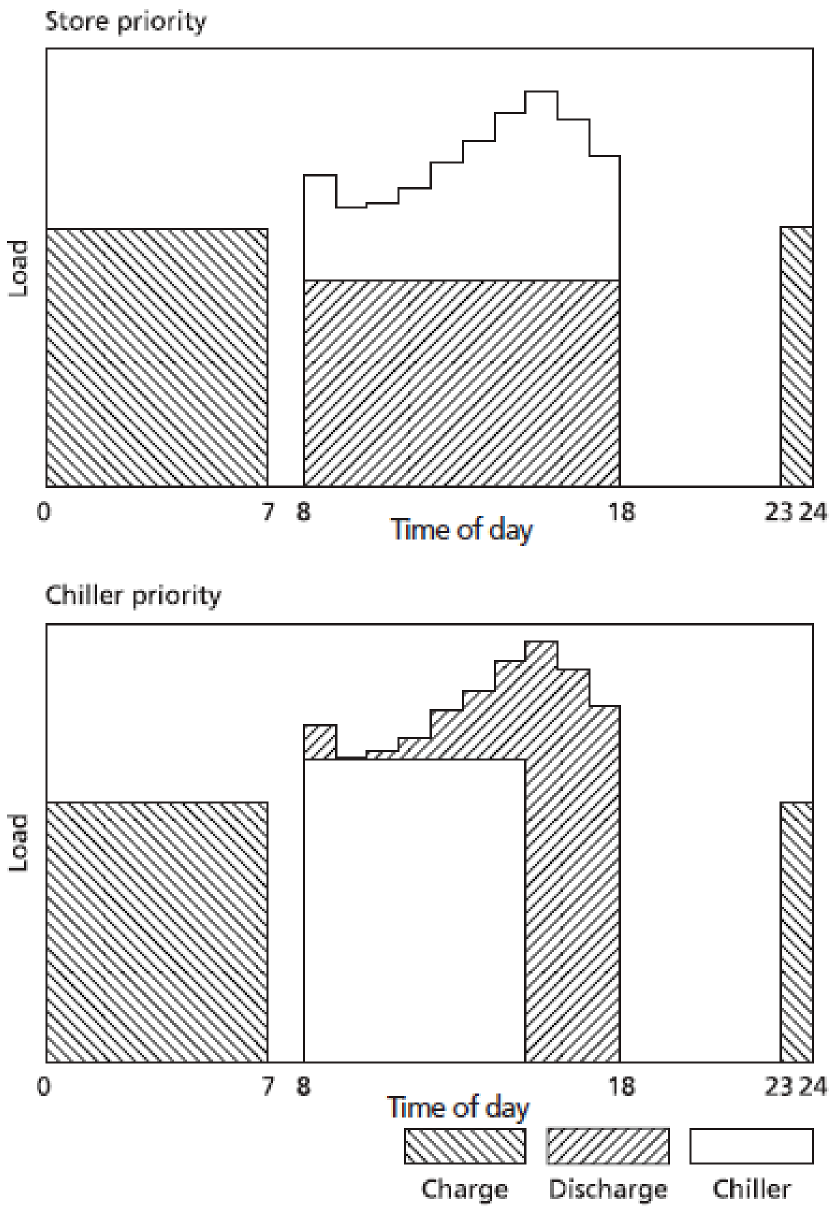


Figure 2-6: Comparison of store priority and chiller priority (Warburton, et al., 2009)

2.4 Available Modelling Software

There are many software packages available for the analysis of energy systems within buildings. Most of these packages are tailored towards the analysis of more standard system designs. For example, heating and cooling systems which use boilers and a conventional chiller could be analysed easily within these packages. It may be difficult or impossible to model more sophisticated system designs within these standard software packages. The analysis of plant items such as CHP units, heat recovery chillers and ice banks and their corresponding control philosophies usually require more specialised software to be used. A detailed evaluation of existing software packages is carried out in Chapter 5.

2.5 Modelling of Ice Banks

Ice banks are difficult to model as the analysis of ice melting and freezing is very complicated and complex. Solutions generally include a three dimensional transient analysis of the temperature distribution within a body of water/ice. These solutions are made more difficult due to the release or absorption of the latent heat of fusion as ice melts or forms. There are also additional complexities including the differing physical properties of ice and water, the melting/freezing rates and the large number of initial and boundary conditions.

Many ice bank and thermal energy storage models exist, ranging from detailed analytical and numerical analyses of particular components within an ice bank to overall economic and thermodynamic optimisation of ice bank systems. A range of these models are discussed below.

Lee and Jones developed a standalone analytical model for an ice-on-coil thermal energy storage (TES) system. The model uses a set of fundamental heat and mass transfer equations to determine both the charging and discharging performance of the ice-on-coil TES. The model predictions of the ice volume and cooling rate were within 5% and 12% of the respective experimental values (Lee & Jones, 1996).

Zhu and Zhang developed an analytical model for an internal melt ice-on-coil tank with horizontal tubes. This model differed from its predecessors as it accounted for the effect of the ice-water density difference on the discharge process. This effect is shown in Figure 2-7. As the ice melts from the inside out, it breaks away from the coil and floats upwards, affecting the heat transfer coefficients around the coil.

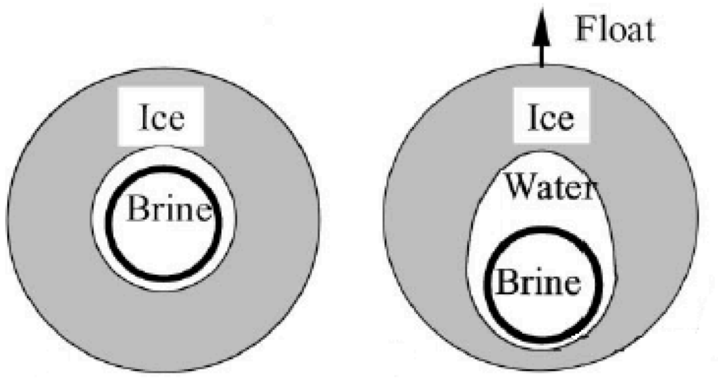


Figure 2-7: Effect of ice-water density difference on discharge process (Zhu & Zhang, 2001)

Soltan and Ardehali developed a numerical model to analyse the water solidification phenomenon for ice-on-coil thermal energy storage application. A finite difference algorithm is used with a cylindrical coordinate system to determine the solidification time of 10mm of ice around a 20mm pipe.

Henze et al. carried out an investigation to determine the performance of four ice bank control strategies: chiller priority control, constant proportion control, store priority control and optimal control for 360 combinations of ice storage systems, chiller types, building and weather types and rate structures. The investigation analysed the change in operating cost, total energy consumption, on-peak demand and off peak demand. Optimal control was defined as that control which minimized the combined energy and demand charge of the electrical utility bill for cooling related and non-cooling related electrical use.

The plant model developed by Henze et al. determined the power consumption of the chiller(s), cooling tower(s), fans and pumps in response to a set of external parameters and set of plant variables. The performance of each plant item was modelled using curve fits to dimensionless data of commercially available equipment. Various limits had to be applied to ensure the numerical stability in the solution of the nonlinear equations describing the ice bank, chiller and air handler. (Henze, et al., 2003)

Sanaye and Shirazi developed an optimisation programme for the economic and thermodynamic optimisation of an ice thermal energy storage system. The programme used a generic algorithm optimisation technique. The objective function of the optimisation programme accounted for the capital and operational costs of the system, a penalty cost for CO_2 emission and costs associated with exergy destruction. The optimisation programme reduced electrical consumption and CO_2 emission by 9% and 9.8% respectively on average when applied to a number of case studies. The average pay back period of the system was found to be 3.4 years. (Sanaye & Shirazi, 2013)

It is clear from the above examples that there is a broad range of existing ice bank models. Some models are designed specifically to analyse a certain phenomenon within the ice bank itself whereas others are designed to justify or optimise the ice banks use within a building's cooling system.

3 The National Gallery of Ireland

This chapter introduces the National Gallery of Ireland and provides information on the current refurbishment works taking place.

3.1 The NGI Building

The National Gallery of Ireland (NGI) houses the Irish national collection of Irish and European fine art. The collection includes some 15,000 paintings, sculptures, works on paper, and *objets d'art* dating from the early thirteenth century through to the mid twentieth century. (NGI, 2014)

The NGI is located in Merrion Square West, Dublin 2 and consists of four main wings: the *Dargan* wing, the *Milltown* wing*,* the *Biet* wing and the *Millennium* wing*.* These wings contain galleries of many shapes and sizes, a restaurant, a gift shop, a lecture theatre, a library, a sculpture garden and various support and plant rooms.

3.2 History of the NGI

The National Gallery of Ireland was officially opened to the public in 1864. The original building consisted solely of what is now the *Dargan* wing. This wing was named after William Dargan, who funded a great exhibition in Dublin in 1853 which sparked the public's interest for art and their desire for a permanent public collection.

The National Gallery of Ireland received a substantial gift from the Countess of Milltown in 1901 including over 200 pictures as well as a collection of silver, furniture and books. This gift was so substantial that a new wing had to be constructed to accommodate it. This new *Milltown* wing was named after the Countess of Milltown to commemorate her generous gift.

The gallery was extended in 1968 with the addition of the *North* wing which included space for a restaurant, a lecture theatre, a library and ten new exhibition galleries. This extension increased the overall hanging space by 50%. This wing is now called the *Biet* wing in acknowledgement of another gift received by the NGI in 1987 from Sir Alfred and Lady Biet.

The most recent addition to the NGI was the M*illennium* wing which was opened in 2002 to accommodate the NGI's growing collection. (NGI, 2014)

3.3 The Refurbishment of the NGI

The much needed refurbishment of the Dargan and Milltown wings is currently under way. The refurbishment aims to address and repair the ageing fabric of the building and upgrade it to meet modern environmental standards. It also aims to provide improvements which will greatly enhance the Gallery's ability to protect, preserve and display its collection.

The Dargan and Milltown wings are currently closed to facilitate this refurbishment. The first phase of the building works, the replacement of the roof of the Dargan wing has already been completed. The next phase is under way and includes a newly designed Merrion Square entrance, improvements to visitor orientation and an extensive upgrade to facilities and services in both wings. The project is expected to continue to 2016. (NGI, 2014)

There are also plans for the addition of a new wing but it is unsure whether this will go ahead.

4 Methodology

This chapter describes the methodology used to evaluate and optimise the low energy plant alternatives for the NGI. Figure 4-1 on the following page shows a simplified process diagram of the methodology used. The simplified process diagram divides the methodology into 6 steps.

The first step was a preparation step and involved finalising the thesis objectives and gathering any available data. Much of the available data was provided by BDP including schematics of the various NGI system designs and an IES model of the NGI building.

The second step was a development step and consisted of four tasks. The first three tasks had to be completed before the fourth task could be started. The first task was to examine and simplify the NGI system designs provided by BDP. The heating, cooling and electrical systems of the NGI were broken down to the following major components: the CHP unit, the ice bank, the heat recovery chiller and the boilers. The make and model of each plant item was provided by BDP which allowed technical data to be sourced from each of the plant item's manufacturers. Each plant item's performances and control options were determined from this data.

The second task was to inspect the IES model of the NGI provided by BDP and identify the relevant zones of the model. The heating cooling and electrical loads were exported from these zones. The IES loads were then manipulated as necessary before the finalised NGI loads were established.

The third task was an evaluation of available software packages. The evaluation determined the package most capable of addressing the finalised thesis objectives, modelling the main components of BDP's system design and using the established loads from BDP's IES model of the NGI.

The forth task could be started once these three tasks had been completed. The fourth task was to develop a model within the chosen software package. The developed model applied the established NGI loads to the simplified NGI system design.

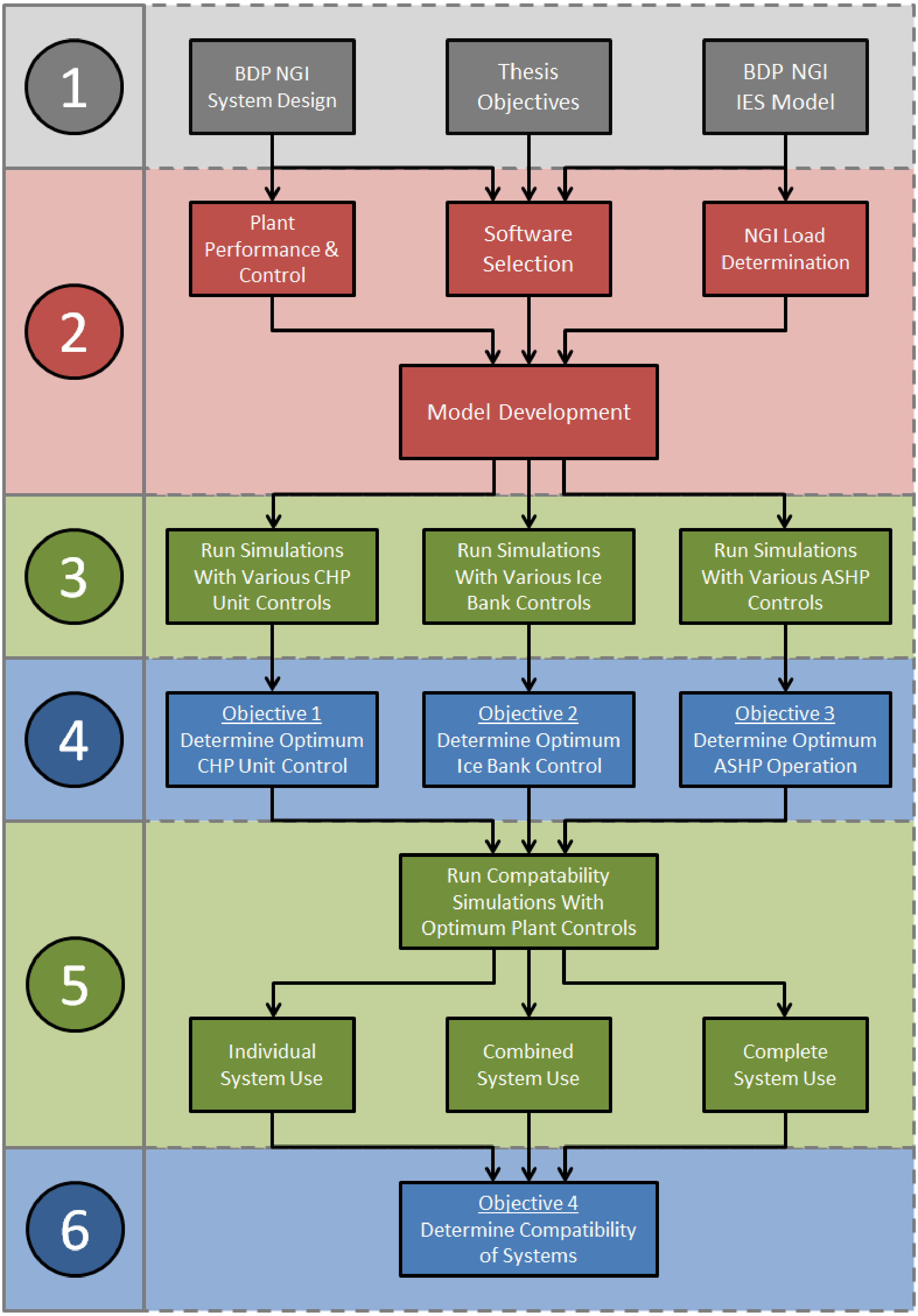


Figure 4-1: Simplified methodology process diagram

Steps three and four were simulation and analysis steps respectively. Simulations were run using the developed model so that the first three thesis objectives could be completed. Simulations were run for each control option available for the plant item in question. The results from the simulations were then analysed to determine the optimum control for the plant item. The variables analysed depended on the plant item being optimised. Example variables that were analysed included the plant item efficiencies and NGI total annual energy cost and CO_2 emissions. Conclusions were drawn for objectives one to three based on the data analysis carried out.

Steps five and six were also simulation and analysis steps respectively. The final objective of analysing the low energy plant items compatibility required each plant item to use its optimum control philosophy. These simulation and analysis steps could therefore not be carried out until objectives one to three had been completed.

Each combination of low energy plant alternatives had to be simulated to determine the compatibility of the plant items. As there were three low energy plant alternatives included in the NGI design, a total of 8 simulations were required to analyse each plant combination. The first simulation used a conventional chiller and boiler to establish a base case which the remainder of the simulations could be compared against. The low energy plant alternatives were simulated individually, in combinations of two and finally altogether. The simulation results were analysed to determine if the combination of plant items achieved the same annual cost and CO_2 savings as the sum of those achieved by the individual use of the plant items. A conclusion was then made on the compatibility of the low energy plant alternatives.

The cost and CO_2 intensities of gas and grid electricity used for the simulations and analyses were provided by BDP and are shown in Table 4-1.

Table 4-1: Gas and grid electricity costs and CO_2 intensities for the NGI building

Fuel	Cost (€/kWh)	CO_2 Intensity (kg/kWh)
Gas	0.035	0.206
Grid Electricity (Day)	0.160	0.414
Grid Electricity (Night)	0.080	0.490

Gas has a cost of approximately 6c/kWh. However, this includes a significant standing charge that is paid irrespective of the amount of gas used. A gas cost of 3.5c/kWh was therefore used so that the cost of the gas consumed could be compared for various simulations. A typical breakdown of a gas bill is shown in Figure 4-2.

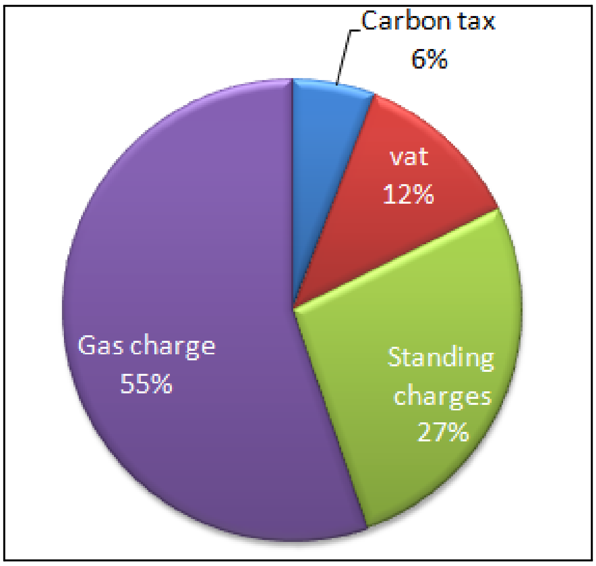


Figure 4-2: Typical gas bill breakdown (BDP)

The grid electricity CO_2 intensities used are average day and night values calculated from data freely available to download from Eirgrid's website (Eirgrid, 2014). The average grid electricity CO_2 intensity calculations are available in Appendix A3.

5 Software Selection

This chapter evaluates a number of available software packages. Figure 5-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

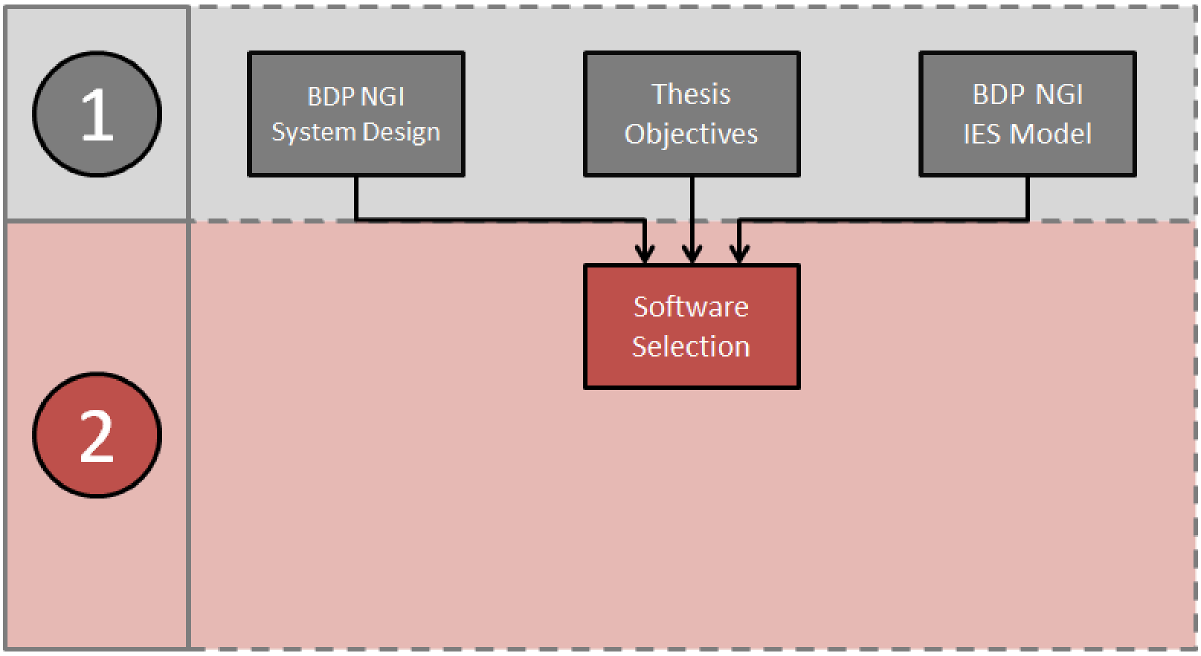


Figure 5-1: Chapter 5 process diagram tasks

5.1 Introduction

There is a wide range of building energy simulation programmes available. Crawley et al. carried out an extensive comparison of twenty major building energy simulation programmes. A selection of these programmes and some more recent programmes are described in the following sections. Each of the software packages are evaluated under a number of evaluation headings. A summary table of each software packages' evaluated ratings is provided in the penultimate section of the chapter. The chosen building energy simulation programme and any additional software used is identified in the final section of the chapter.

5.2 EnergyPlus

EnergyPlus is a whole building energy simulation programme that is used by architects, engineers and researchers to model energy and water use in buildings. It is a modular, structured software tool based on the most popular features and capabilities of previous software packages BLAST and DOE-2.1E.

EnergyPlus is not a user interface; it is intended to be the simulation engine around which a third-party interface can be wrapped. The source code of EnergyPlus is available and open for public inspection or revision. EnergyPlus is intended to be developer friendly so that users may develop new modules or tailor existing modules to their specific needs. (EnergyPlus, 2013)

EnergyPlus models heating, cooling, lighting, ventilation, other energy flows and water use. It is primarily a simulation engine that uses text files as inputs and outputs. EnergyPlus has two basic components, a heat and mass balance simulation module and a building systems simulation module. Loads are calculated by the heat and mass balance simulation module at a specific time step and passed to the building systems simulation module at the same time step. The building systems simulation module, with a variable time step, then calculates heating and cooling system and plant and electrical system response. (Crawley, et al., 2005)

EnergyPlus is available to download online at no charge. There are detailed user guides, application guides and developer guides available online.

5.3 DesignBuilder

DesignBuilder provides a graphical user interface to the EnergyPlus simulation engine. DesignBuilder’s interface is well organised around several tabbed views. The main *Layout* tab is where the three dimensional geometric model of the building is constructed. Other tabs then allow various model parameters to be attached to the building model such as the construction of the model’s elements, lighting levels and profiles, HVAC systems, occupant information etc. A nice feature of DesignBuilder is its *data inheritance* mechanism which allows global changes be made and applied to only relevant parts of the model.

Advanced design options such as daylight control, natural ventilation, double facades, chilled beams and heated floors can be assessed for their impact on the building environmental performance, comfort, cost and daylight availability. DesignBuilder includes a large database of common constructions, glazing systems, usage patterns, HVACX and lighting systems and ASHRAE international weather data. (DesignBuilder Software Ltd., 2014)

The templates available in DesignBuilder can be used directly or altered to a user's specific needs. However, there are no existing templates for advanced HVAC components such as CHP or ice banks. DesignBuilder is more suited to standard HVAC designs; the user must revert to EnergyPlus to model more advanced HVAC systems.

Design Builder offers extensive free online video tutorials covering basic to advanced features of the programme. There are a number of Design Builder licenses available at UCD.

5.4 IDA ICE

IDA Indoor Climate Energy (IDA ICE) is based on a general simulation platform for modular systems. Physical systems are described using symbolic equations stated in either or both of the simulation languages Neutral Model Format (NMF) or Modelica. User defined tolerances control solution accuracy, allowing complete isolation of numerical errors from modelling approximations. Efficient differential algebraic equation solvers are used to achieve a close to linear relationship between problem size and execution time. This approach is beneficial to the user for a number of reasons:

- The mathematical model is fully transparent to the user and all of the variables, parameters, equations etc. can be inspected.
- Model extensions can be purchased or developed and added as required.

IDA ICE was developed within a northern European engineering culture. As a result, it is particularly good for modelling displacement ventilation, active chilled beams, radiative devices and air and water based slab systems. A special strength is realistic modelling of controls which allows for the study of local loop behaviour in a whole building context.

IDA ICE offers different user interfaces to users with varying levels of experience. A *Wizard* interface is available for beginners right though to an *Advanced* or

NMF/Modeica programming interface for advanced users and programmers. (Crawley, et al., 2005)

There are online manuals available for users of IDA ICE software. There are no IDA ICE licenses available from UCD.

5.5 IES VE

Integrated Environmental Solutions (IES) Virtual Environment (VE) provides the user with a range of design orientated building analysis applications within a single software package. At the core of the model is a three dimensional geometric model of the building. Specific applications attach relevant data to this model and use different user interfaces tailored to the specific design task. The single model environment allows for easy data exchange between applications.

Applications are available for tasks ranging from simple calculation of the building's steady state thermal loads to detailed computational fluid dynamics within particular areas of the building. Results are easily analysed and interrogated in an application which presents the data graphically at various levels of aggregation and includes functions for statistical analysis. Results can also be exported for use in other software packages. (Crawley, et al., 2005)

There are detailed free user guides available online for the various applications within IES. These guides explain how the various applications operate and offer guidance on how to use them. These guides provide a certain level of transparency to the user but there is little allowance for customisation of the model or applications. (IES, 2014)

IES VE requires a license to download and use. There are no licenses available from UCD and the price of a student license is €60. (IES, 2014)

5.6 TRNSYS

TRNSYS is a transient system simulation programme. It has a modular structure and is designed to solve complex energy system problems by breaking the problem down into a series of smaller components which are referred to as *Types*. These components may be as simple as a pipe section or as complicated as a multi-zone building model. Each component contains a series of inputs and outputs. The outputs of each component are determined at each time step from inputs at that time step and the source code attached to the component. (Crawley, et al., 2005)

The source code of each component contains the mathematical equations which describe the component and some additional code which describes how TRNSYS handles it. TRSNSYS contains an extensive library of components for the creation of HVAC systems. It also contains components for incorporating other software such as Mathlab or Excel into the model. TRNSYS is very transparent; the source code of existing components can be interrogated by the user to identify exactly how each component operates.

New components are easily created within TRNSYS. The source code for these new components must be compiled into a dynamic link library (DLL) using external software. Source code may be written in any programming language provided that there is a complier available that is capable of creating a DLL. This allows any HVAC equipment that can be described mathematically to be modelled within TRNSYS.

A visual interface known as TRNSYS Simulation Studio allows the user to configure and assemble components. Systems are created by connecting the outputs from one type to the inputs of another type. Any system variable can be plotted onscreen in real time as the simulation progresses. The system variables can also be exported as text files or opened directly in Excel.

There are extensive manuals and documentation available for TRNSYS users, including guides on how to use the programme, descriptions and mathematical references of existing components and guides on how to create new components.

There are a number of TRNSYS license available from UCD.

5.7 Software Ratings

Each of the software packages described in the previous sections were evaluated under 11 evaluation headings. Each heading was assigned a weighting between 1 and 3 depending on its importance. The evaluation headings used were those deemed most relevant by the author. An evaluation heading with a weighting of 1 was not a very important consideration whereas an evaluation heading with a weighting of 3 was a vitally important consideration. Each software package was assigned a rating under each evaluation heading. The ratings assigned to each software package were the author's personnel opinion. The rating system used ranged from 0 to 5 and is shown in Figure 5-2.

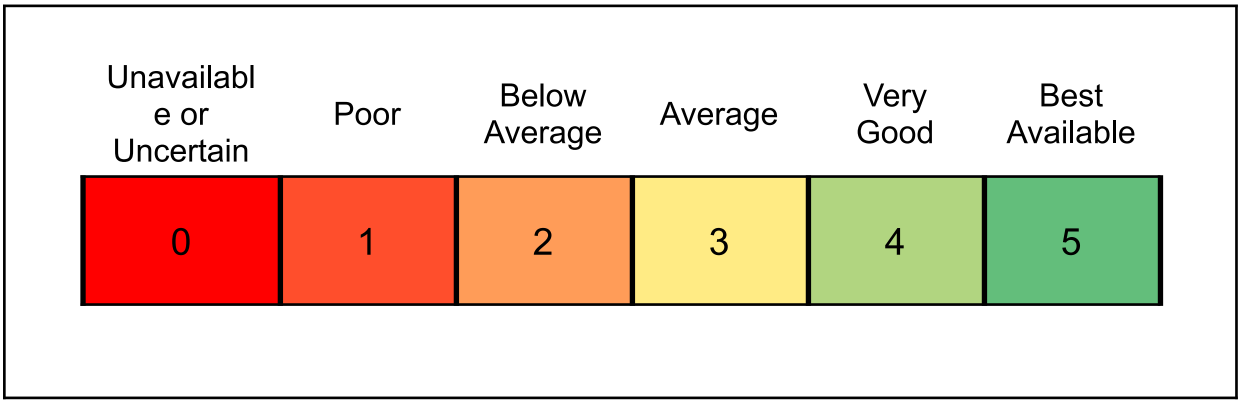


Figure 5-2: Software package ratings used

The total rating for each software package was determined by summing the weighted ratings of each evaluation heading. The total rating was out of a maximum of one hundred. The software packages' ratings under each evaluation heading and their total ratings are summarised in Table 5-1.

Table 5-1: Software selection summary

Evaluation Heading	Weight	Energy Plus	Design Builder	IDA ICE	IES VE	TRNSYS
Incorporate low energy plant alternatives	3	5	0	0	0	5
Analysis capabilities	3	5	4	4	4	5
Use of IES loads	3	4	0	0	5	4
Difficulty of model construction	2	1	3	3	4	2
Transparency	2	5	3	4	3	5
Customisability	2	5	2	0	2	5
Documentation & video tutorials	1	4	5	3	4	4
Additional software requirements	1	2	4	0	4	2
Support available at UCD	1	4	4	1	2	4
User friendliness	1	2	5	5	5	3
Author’s knowledge and abilities	1	1	3	1	5	1
Rating (out of 100)		75	44	31	60	77

It can be seen from Table 5-1 that the software package which scored highest was TRNSYS, followed closely by EnergyPlus. The only difference between TRNSYS and EnergyPlus was the difficulty of model construction and user friendliness. TRNSYS's simulation studio gives it a slight advantage over EnergyPlus under each of these evaluation headings. Both TRNSYS and EnergyPlus scored well under the first three evaluation headings which are the most important. They are both capable of modelling and analysing the low energy plant alternative used in the NGI. They can also use loads exported from the IES model within their own models.

DesignBuilder, IDA ICE and IES VE are very similar software packages. IES VE scored highest out of the three simply because a model already existed which could be used. Incorporating IES loads was therefore not an issue and it would not be difficult to build the model as the existing model could simply be added to. IDA ICE scored poorest of the three as there was uncertainty regarding a few of the evaluation headings. Most importantly, the three software packages are not capable of incorporating specific performances and control philosophies associated with the low energy plant alternatives of the NGI. These three software packages could not fulfil the thesis objectives and were therefore ruled out of the software selection process.

5.8 Selected Software

The primary software selected to evaluate and optimise the low energy plant alternatives of the NGI was TRNSYS. TRNSYS was selected as it is transparent and allows for the development of components specific to the NGI's plant items. Its ability to track any variable through output text files or onscreen plotting is ideal for analysis purposes as well as for troubleshooting problems.

A number of secondary software packages were also used including; an integrated development environment (IDE), IES VE and Excel. The IDE used was Microsoft Visual Studio. This IDE provided the facilities to create and compile the source code for any new components made for TRNSYS. IES VE was used to determine the NGI heating, cooling and electrical load profiles. TRNSYS has the ability to determine these load profiles but requires the building to be built within TRNSYS. The loads were instead exported from the existing IES model. The exported loads from the IES model were imported to Excel. Data was exchanged between Excel and TRNSYS via text files. Excel was used for both inputting data to the TRNSYS model and for analysing the outputs from the TRNSYS model.

6 Plant Performance and Control

This chapter determines the performance and control options of each of the NGI's low energy plant items. Figure 6-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

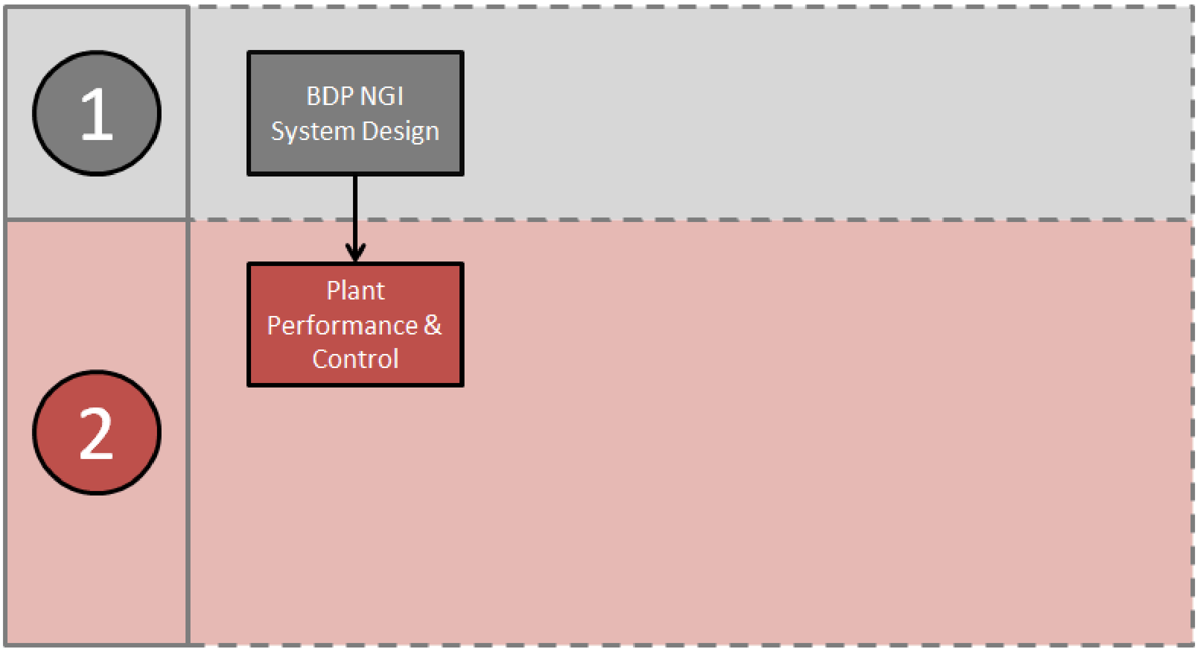


Figure 6-1: Chapter 6 process diagram tasks

6.1 Introduction

Models were developed for the NGI's low energy plant items; the CHP unit, the heat recovery chiller and the ice banks. The models developed were specific to the actual plant items used for the NGI system. This chapter briefly explains the plant item's purpose, the method used to determine its performance and the control options available for the item within the TRNSYS model. Each plant item had different specific modelling and control requirements. Various approaches were taken to determine the performance of each plant item. In each case, BDP and the relevant manufacturer were consulted on the modelled performance used for their corresponding plant item.

6.2 CHP Unit

The CHP unit provides some of the NGI's electrical load and heating load. The CHP unit generates heat at 82°C. The CHP unit can therefore provide the NGI's higher temperature heating load or its lower temperature heating load through a heat exchanger. The CHP unit satisfies the higher temperature heating load before satisfying the lower temperature heating load so that it doesn't *steal* the load available to the heat recovery chiller.

The CHP unit used in the NGI is an *E150 CHP Plant*, manufactured by *ENER-G*. Further details of the CHP unit are available in Appendix B1.

6.2.1 Performance

The modelled CHP unit performance was based on a Diesel Electric Generator's (DEG) performance from the standard TRNSYS component library. The fuel consumption of the CHP unit was determined using equation (6-1).

$$V_{fuel} = a + b * \frac{P_{CHP}}{P_{RATED}} \; [m^3/s] \qquad (6\text{-}1)$$

The equation coefficients *a* and *b* in equation (6-1) were determined from two sets of performance data. Each performance data set gave the power output and corresponding total heat output of the CHP unit. The fuel consumption for each data set was determined using equations (6-2) and (6-3) consecutively.

$$\eta_{elec} = \frac{P_{CHP}}{P_{CHP}+Q_{Total}} \quad [\%] \qquad (6\text{-}2)$$

$$V_{fuel} = \frac{P_{CHP}}{\rho_{fuel} * \eta_{elec} * LHV_{fuel}} \quad [m^3/s] \qquad (6\text{-}3)$$

The first performance data set was taken from the equipment specification provided by BDP. The values from BDP's equipment schedule were quoted from the CHP manufacturer. However, the manufacturer quoted the useful heat output of the CHP unit whereas the total heat output was required. It was assumed that the CHP unit loses a constant 20% of its total heat output. This allowed the total heat output of the CHP unit to be determined from the quoted useful heat output. Table 6-1 shows the two performance data sets used to determine the equation coefficients *a* and *b* in equation (6-1).

Table 6-1: CHP performance data sets

Performance Set	Source	$P_{CHP}(kW)$	$Q_{Total}\ (kW)$
1	BDP equipment schedule (manufacturer's data)	151	288.75 (231/0.8)
2	TRNSYS standard DEG component	65	145.1

The fuel properties used in equation (6-3) are for natural gas and are given in Table 6-2.

Table 6-2: Natural gas properties

Fuel Property	Equation Symbol	Value	Unit
Density	ρ_{fuel}	0.83	$kg/m\text{^}3$
Lower Heating Value	LHV_{fuel}	47,700	kJ/kg

The electrical efficiency and total heat output of the CHP unit at any power output could be calculated once the coefficients *a* and *b* from equation (6-1) had been determined. The electrical efficiency and total heat output of the CHP unit were calculated using equations (6-4) and (6-5) respectively. Assuming the CHP losses 20% of its total heat generated, the useful heat of the CHP unit is given by equation (6-6).

$$\eta_{elec} = \frac{P_{CHP}}{\rho_{fuel}*V_{fuel}*LHV_{fuel}}\ [\%] \quad \textbf{(6-4)}$$

$$Q_{Total} = P_{CHP} * \frac{1-\eta_{elec}}{\eta_{elec}}\ [kW] \quad \textbf{(6-5)}$$

$$Q_{Useful} = Q_{Total} * (1.0\ -\ 0.2)\ [kW] \quad \textbf{(6-6)}$$

The resulting CHP unit performance is given in Figure 6-2. It can be seen that the electrical efficiency is very poor at low CHP unit power outputs. It rises dramatically as the power output of the CHP unit increases and reaches a maximum at approximately 34% when the CHP unit is at its maximum power output of 150kWe. The useful heat output of the CHP unit rises linearly with its power output.

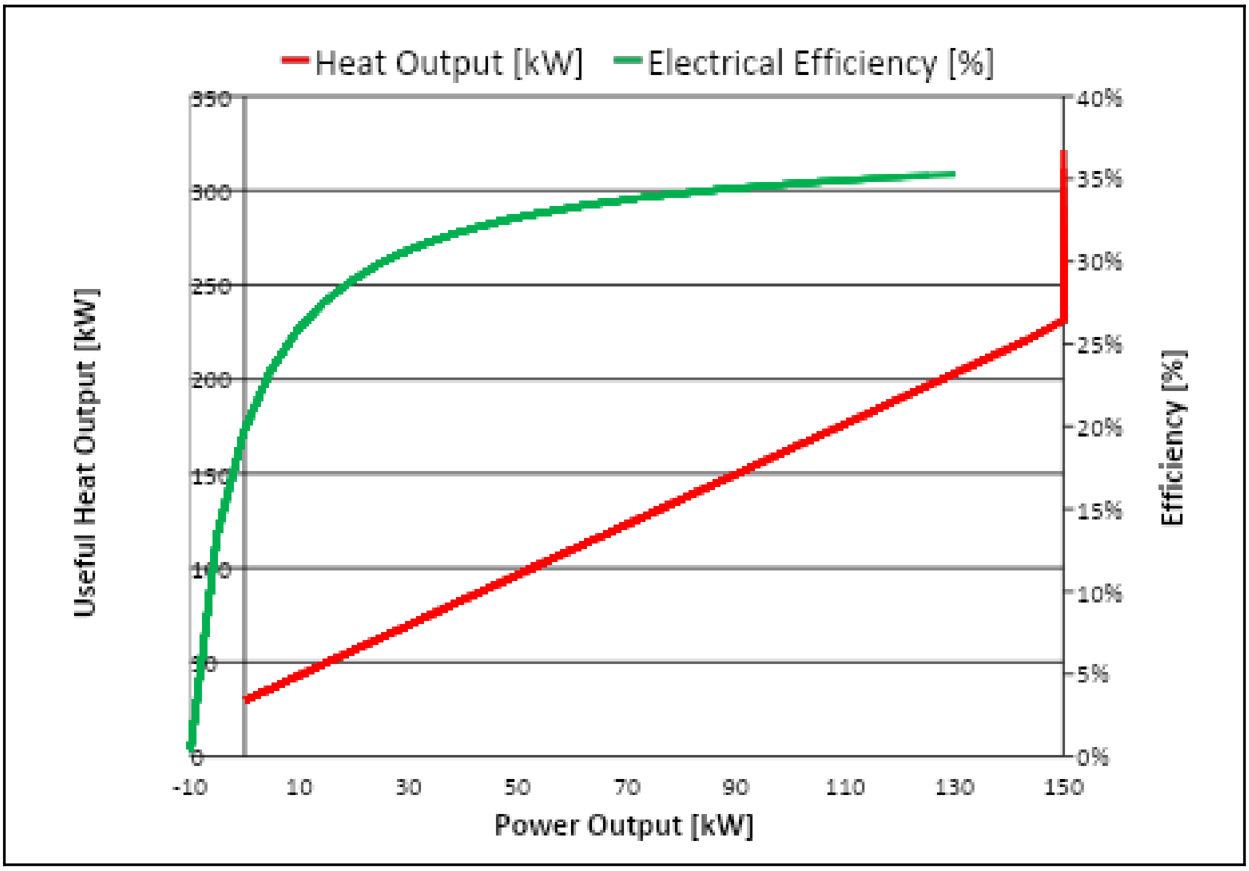


Figure 6-2: Modelled CHP unit performance

6.2.2 Control Options

The CHP unit used in the model has two control options. The control options are shown in Figure 6-3 and Figure 6-4 respectively as simplified flow diagrams.

The first control option gives the user more control of when the CHP unit will operate. The CHP unit will only operate under this control option if the electrical load exceeds a minimum CHP unit power output set by the user. This minimum CHP unit power output is used to limit the drop in the unit's electrical efficiency. The user can then select whether the CHP unit operates:

- at all times
- only during on-peak electrical tariffs

- only if all of the CHP unit’s heat can be used
- at all times during on peak electrical tariffs and only if all of the CHP unit’s heat can be used during off-peak electrical tariffs

The second control option automatically selects the optimum CHP unit operation in order to minimise the cost of running the unit or the CO_2 emissions from running the unit. With this control option, the user simply selects which variable is to be minimised. The CHP unit operates according to the optimum control philosophy outlined in Chapter 9.

Both CHP unit control options are influenced by the following external simulation settings:

- The CHP unit may be given heat priority over the heat recovery chiller. This affects the heating load available to the CHP unit
- The CHP unit may be switched off due to a set maintenance period
- The CHP unit may be set to unavailable, preventing its use

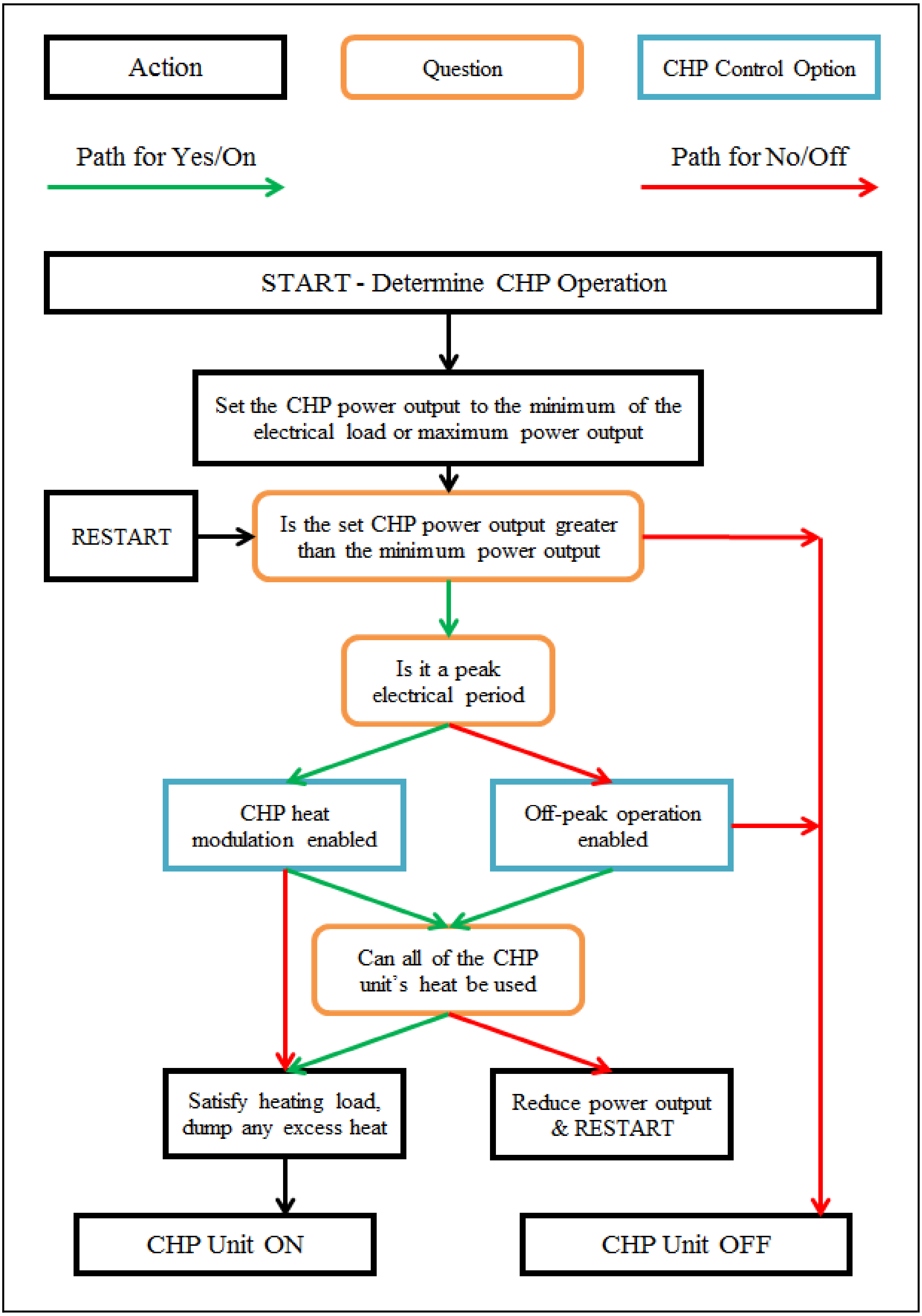


Figure 6-3: CHP unit control option 1

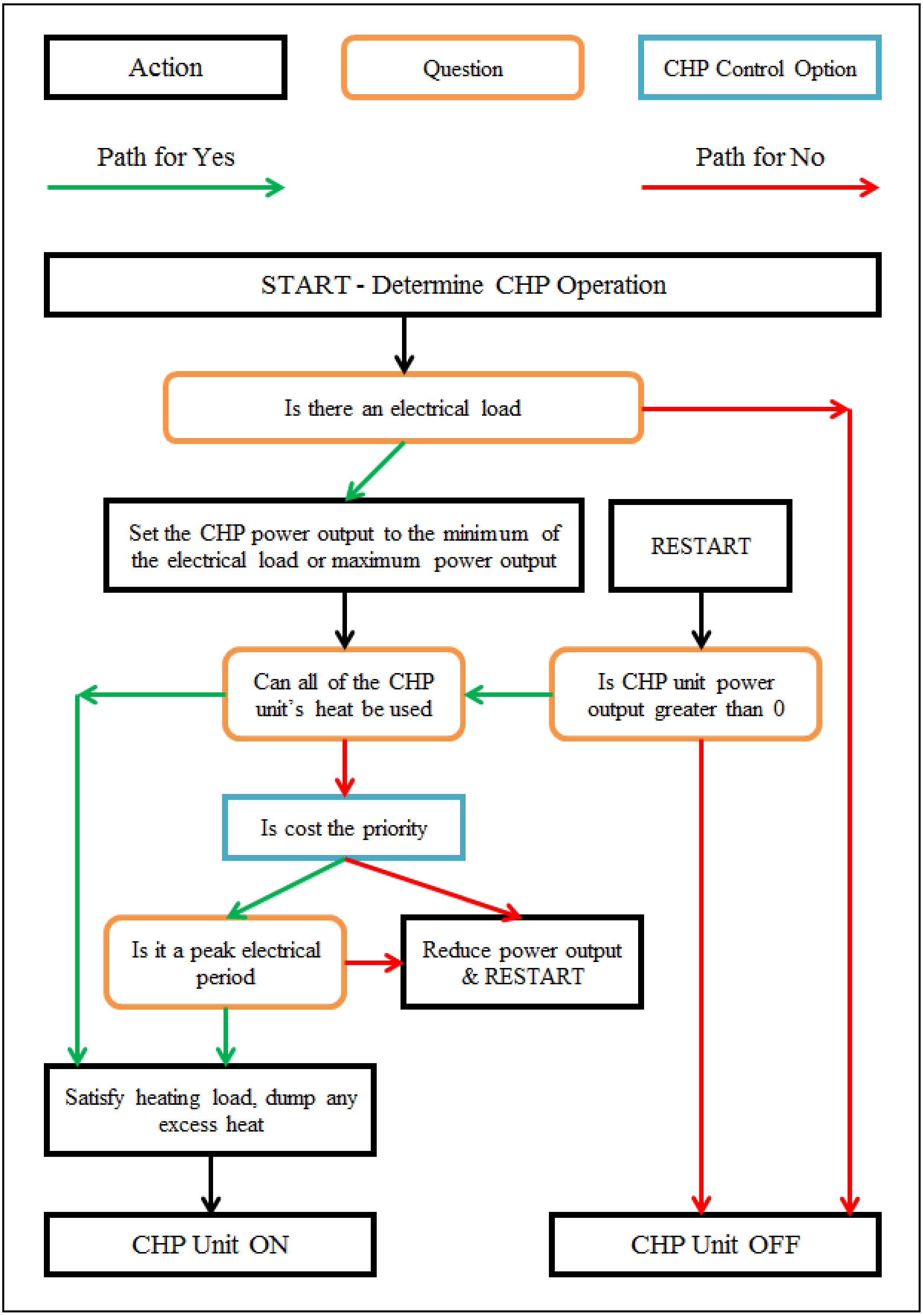


Figure 6-4: CHP unit control option 2

6.3 Heat Recovery Chiller

The heat recovery chiller provides the NGI's cooling load and the ice bank's charging load. Any heat that is recovered from the cooling process contributes to the NGI's available lower temperature heating load. The chiller can also operate as an air source heat pump (ASHP) and provide the entire lower temperature heating load regardless of the cooling load available.

The heat recovery chiller used in the NGI is an *AERMEC 1800A*. Further details of the heat recovery chiller are available in the Appendix B2.

6.3.1 Operating Modes

The modelled heat recovery chiller can operate in five operating modes: cooling only, heating only, total recovery, cooling main and heating main. The modelled chiller has two evaporators and two condensers. The *CHW Evaporator* provides the cooling to the chilled water, the *LTHW condenser* provides the heating to the low temperature hot water and the *Ambient Evaporator* and *Ambient Condenser* use the ambient air as a heat source and sink respectively. The use of the chiller's evaporators and condensers for each operating mode are summarised in Table 6-3.

Table 6-3: Chiller evaporator and condenser use for each operating mode

Operating Mode	CHW Evaporator	LTHW Condenser	Ambient Evaporator	Ambient Condenser
Cooling Only	X			X
Heating Only		X	X	
Total Recovery	X	X		
Cooling Main	X	X		X
Heating Main	X	X	X	
An X indicates the evaporator/condenser's use for the specified operating mode				

<u>Cooling Only Mode</u>

The chiller operates in cooling only mode when there is a cooling load but no heating load available. The chiller provides the required amount of cooling and dumps any recoverable heat to the ambient. The performance of the chiller in cooling only mode depends on the ambient air temperature and the chilled water flow temperature required.

Heating Only Mode

The chiller operates in heating only mode when there is a heating load but no cooling load present. The ASHP feature of the chiller must be enabled to allow the chiller to operate in this mode. The chiller uses the ambient air as a heat source to provide the heating load required. The chiller's heat output modulates so that the ambient air temperature after the chiller's condenser does not drop below 6°C. If the chiller's heat output must be modulated for this reason, alternative heating sources must provide the remainder of the lower temperature heating load.

Total Recovery

In total recovery mode, the chiller provides the required cooling load and the available heating load is sufficient to use all of the recovered heat. The chiller is driven by the cooling load and only some of the heating load is provided when operating in total recovery mode. The chiller only operates in total recovery mode when it is prevented from operating in heating main mode.

Cooling Main Mode

In cooling main mode, the cooling load is larger than the available heating load. The chiller provides the required cooling load and the recovered heat is sufficient to meet the entire heating load. Some of the recoverable heat must be dumped to the ambient. The chiller uses one evaporator and two condensers in cooling main mode.

Heating Main Mode

In heating main mode, the recovered heat from providing the entire cooling load is not sufficient to meet the entire heating load. The chiller uses the ambient air as a source of heat to meet the remainder of the heating load. The chiller must therefore be enabled to operate as an ASHP. Similarly to heating only mode, the ambient air temperature after the chiller's ambient condenser must be greater than 6°C or the chiller reduces its heat output and eventually reverts back to total recovery mode. The chiller uses two evaporators and one condenser in heating main mode.

6.3.2 Performance

The efficiency of the chiller is defined differently depending on its mode of operation. In cooling only mode, the chiller's energy efficiency ratio (EER) is used. In heating only mode, the chiller's coefficient of performance (COP) is used. In total recovery mode, the chiller's total efficiency ratio (TER) is used. The EER, COP and TER of the chiller are defined according to equations (6-7), (6-8) and (6-9). The analyses in later chapters use COP when referring to any of these efficiency definitions.

$$EER = \frac{Cooling\ provided\ by\ chiller}{Electrical\ power\ consumption\ of\ chiller}\quad [W/W] \tag{6-7}$$

$$COP = \frac{Heating\ provided\ by\ chiller}{Electrical\ power\ consumption\ of\ chiller}\quad [W/W] \tag{6-8}$$

$$TER = \frac{Cooling\ and\ heating\ provided\ by\ chiller}{Electrical\ power\ consumption\ of\ chiller}\quad [W/W] \tag{6-9}$$

The performance of the chiller depends on its operating mode. A technical data sheet provided by the chiller's manufacturer gave nominal performance figures for cooling only mode, heating only mode and total recovery mode. Correction factor (CF) graphs were also provided to determine the performance at varying ambient air temperatures, CHW and LTHW setpoint temperatures and CHW glycol percentages. A sample report of an AERMEC chiller's performance at various cooling loads allowed correction factors for the part load ratio of the chiller to be developed. No data was provided for cooling only and heating only modes. The technical data sheet and sample report are provided in Appendix B2.

The EER of the chiller in cooling only mode, the COP of the chiller in heating only mode and the TER of the chiller in total recovery mode were calculated using equations (6-10), (6-11) and (6-12) respectively.

$$EER = EER_{nom} * PLR\ CF * \frac{Cooling\ Capacity\ CF}{Input\ Power\ CF} * Glycol\ CF\quad [W/W] \tag{6-10}$$

$$COP = COP_{nom} * PLR\ CF * \frac{Heating\ Capacity\ CF}{Input\ Power\ CF} * Glycol\ CF\quad [W/W] \tag{6-11}$$

$$TER = TER_{nom} * PLR\,CF * \frac{Recovered\,Power\,CF}{Input\,Power\,CF} * Glycol\,CF \quad [W/W] \tag{6-12}$$

The electrical power consumption of the chiller could be calculated once the relevant chiller efficiency had been determined. For total recovery mode, the amount of heat recovered *(Q_{LTHW})* could be calculated from knowledge of the cooling load provided *(Q_{CHW})*, overall compressor efficiency *($\eta_{Compressor}$)* and electrical consumption of the chiller *($P_{Chiller}$)* using equation (6-13).

$$Q_{LTHW} = Q_{CHW} + \eta_{Compressor} * P_{Chiller} \tag{6-13}$$

The overall compressor efficiency was assumed to remain constant and was calculated using the nominal data provided by the manufacturer for total recovery mode.

<u>Cooling Only Mode</u>

The performance of the chiller in cooling only mode depends on the cooling load to be met by the chiller, the ambient air temperature and the evaporator or CHW setpoint temperature. Figure 6-5 shows the chiller performance in cooling only mode for various ambient air temperatures and CHW setpoint temperatures of (a) 6°C and (b) -6°C.

The CHW setpoint temperature is 6°C when the NGI cooling load is provided by the chiller alone and is -6°C when the chiller charges the ice bank. It can be seen that the EER of the chiller decreases when the CHW setpoint temperature decreases or the ambient air temperature increases. This is because the temperature lift required by the chiller increases. The higher the temperature lift required by the chiller, the more work the compressor must do for the same amount of cooling provided. The EER of the chiller also decreases at lower cooling loads or PLRs due to less efficient operation of the chiller's compressors.

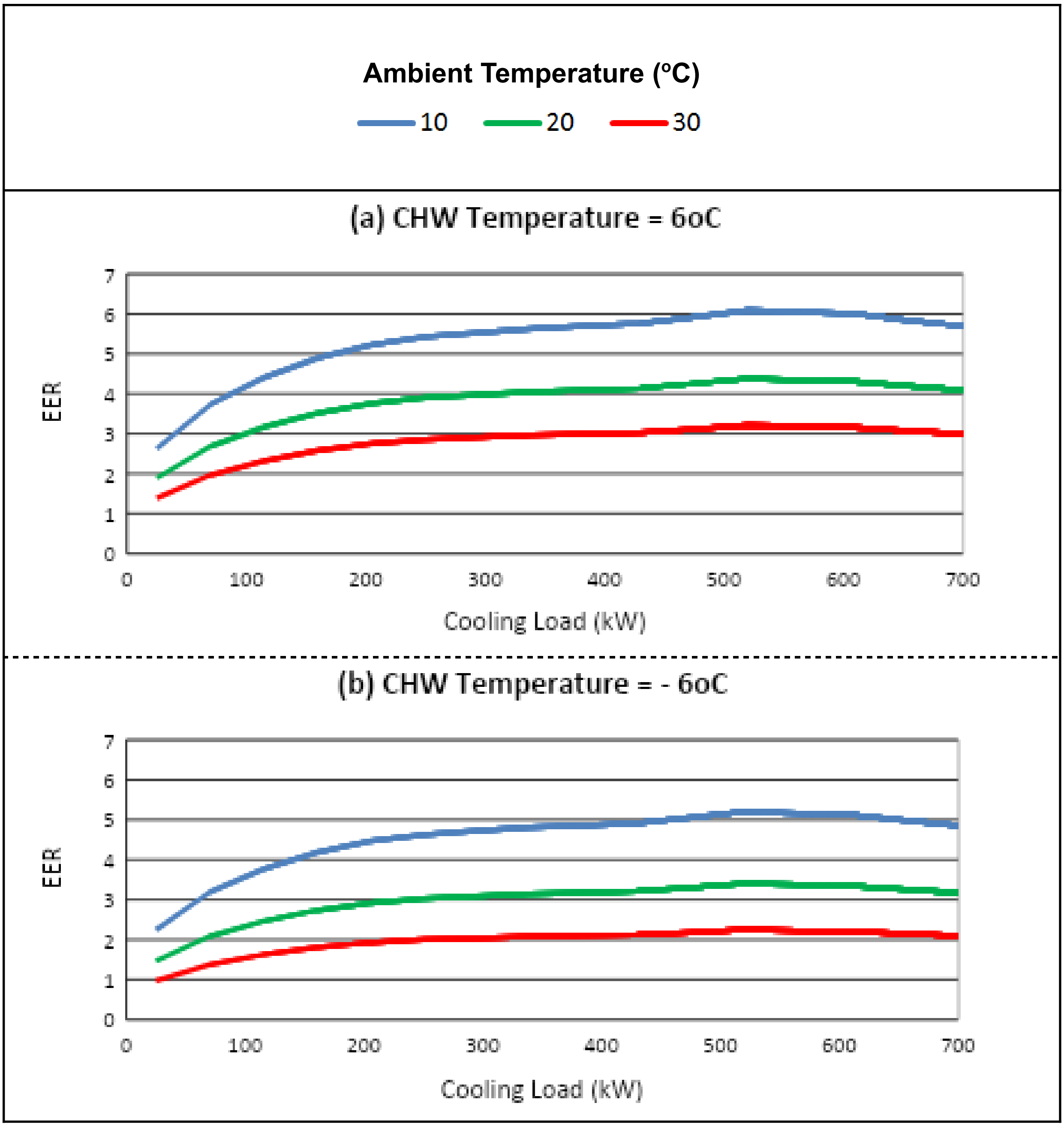


Figure 6-5: Chiller performance in cooling only mode

<u>Heating Only Mode</u>

The performance of the chiller in heating only mode depends on the heating load to be met by the chiller, the ambient air temperature and the condenser or LTHW setpoint temperature. Figure 6-6 shows the chiller performance in heating only mode for various ambient air temperatures and a LTHW setpoint temperature of 40°C. It can be seen that the COP of the chiller decreases at smaller heating loads or PLRs.

It also increases as the ambient air temperature approaches the LTHW setpoint temperature because the temperature lift required by the chiller decreases. However, the ambient air temperature has less of an effect on the COP of the chiller as it increases.

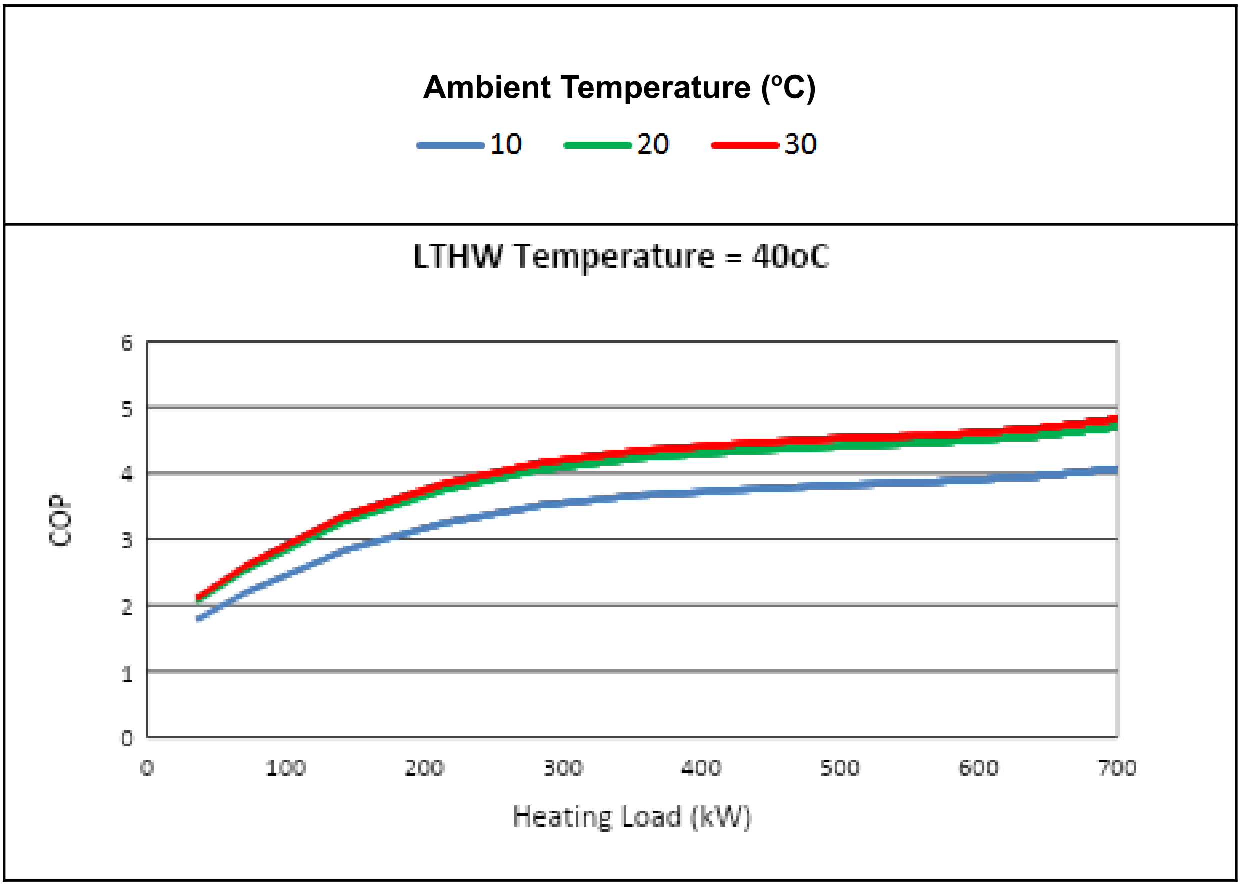


Figure 6-6: Chiller performance in heating only mode

<u>Total Recovery Mode</u>

The performance of the chiller in total recovery mode depends on the cooling load to be met by the chiller and the CHW and LTHW setpoint temperatures. Figure 6-7 shows the chiller performance in total recovery mode for a LTHW setpoint temperature of 40°C and CHW setpoint temperatures of 6°C and -6°C respectively. Similarly to the heating only and cooling only modes, it can be seen that the TER of the chiller decreases at smaller cooling loads and higher temperature lifts. By contrast, the recoverable heat increases at smaller cooling loads and higher temperature lifts. This is because more heat is produced as the chiller does more work.

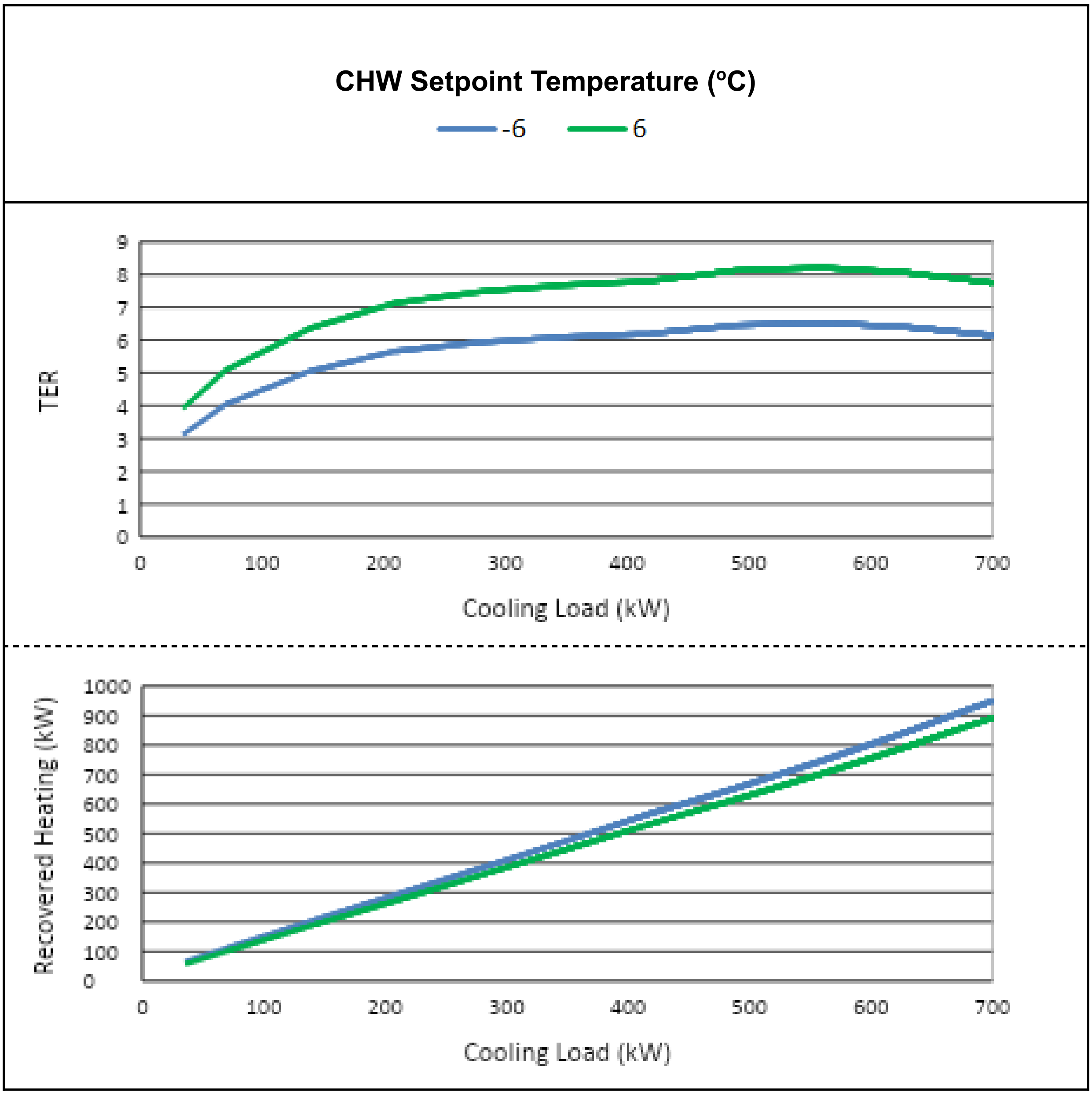


Figure 6-7: Chiller performance in total recovery mode

<u>Cooling Main Mode</u>

When the chiller operates in cooling main mode, the model effectively assumes that there are two imaginary chillers operating. The first imaginary chiller performs in total recovery mode and provides just enough cooling so that the recovered heat matches the heating load perfectly. The second imaginary chiller performs in cooling only mode and provides the remainder of the cooling load. The actual chiller TER is then determined by summing the combined heating and cooling loads provided by the two imaginary chillers and dividing by the combined electrical power consumptions of the two imaginary chillers.

Heating Main Mode

A similar method is used to determine the performance of the chiller in heating main mode. In this case, the first imaginary chiller performs in total recovery mode and provides just enough heating so that the cooling provided matches the cooling load perfectly. The second imaginary chiller performs in heating only mode and provides the remainder of the heating load. The actual chiller TER is then determined using the same method as for cooling main mode.

6.3.3 Control

The chiller model automatically determines which operating mode to use depending on the NGI heating and cooling loads present. The heating load available to the chiller is affected by the CHP heat priority setting of the simulation. There is less heat available to the chiller if the user gives the CHP unit's heat priority over the chiller heat. The chiller operates in cooling only mode and cooling main mode more frequently as a result.

The CHW setpoint temperatures are determined automatically by the chiller model. The ice bank model communicates to the chiller model when it is charging and discharging. The CHW flow and return temperatures through the chiller are given in Table 6-4.

Table 6-4: Chiller CHW temperatures

Ice Bank Operation	CHW Flow Temperature (°C)	CHW Return Temperature (°C)
Charging	-6	-2
Discharging	3	9
Standby	6	12

The user can enable or disable the operation of the ASHP during the simulation. This setting can be applied at all times or just during on peak electrical hours. The operation of the ASHP is discussed in detail in Chapter 11.

The user can disable the heat recovery feature of the chiller to model a conventional chiller. The conventional chiller is limited to operating in cooling only mode. This feature is useful for determining the benefits of including a heat recovery chiller over a conventional chiller in the NGI system. The user also sets the chiller's availability and scheduled downtimes.

6.4 Ice Bank

The ice bank is used to shift the NGI's cooling load from the daytime to the night time. This is done to reduce the chiller electrical load during the day when the grid electrical tariffs are high. The ice bank can also reduce the maximum electrical demand on the grid which can decrease the risk of exceeding the NGI's maximum import capacity (MIC).

The ice bank used in the NGI is a *Calmac 1190C*. Further details of the ice bank are available from Calmac's website (Calmac, 2014).

6.4.1 Performance

Ice banks are extremely complex to model in detail. The cooling provided by the ice bank or the charging of the ice bank depends on many factors including the inlet and outlet chilled water temperatures, the chilled water flow rate, the type and arrangement of internal heat exchanger, the thickness of ice present and the ice bank construction.

Many ice bank models exist as described in Chapter 2.5. The ice bank for the TRNSYS model of the NGI plant system does not need to be overly complex. The ice bank model developed was based on an analysis carried out by *Calmac* for an ice bank system in Dundalk. This analysis is available in Appendix B3.

Similarly to the ice bank in the Calmac analysis, a simplified device which simply accepts or rejects cooling potential was used for the ice bank model. A sample of this simplified ice bank's performance over a day is given in Figure 6-8. The following data and assumptions are used in the sample:

- The charging period is between 23:00 to 08:00
- The discharging period is between 08:00 to 23:00

- Cooling loads are only present between 08:00 to 23:00
- The ice bank is to provide the entire cooling load
- The chiller is to fully charge the ice bank over the entire charging period
- The ice bank stored capacity is 1000kWh
- There are no losses from the ice bank

= Charging Period (blue) = Discharging Period (red)

Hour of Day	Cooling Load (kW)	Chiller Load (kW)	Ice Bank Load (kW)	Ice Bank Stored Cooling Potential at beginning of hour (kWh)
0	0	100	0	200
1	0	100	0	300
2	0	100	0	400
3	0	100	0	500
4	0	100	0	600
5	0	100	0	700
6	0	100	0	800
7	0	100	0	900
8	20	0	20	1000
9	30	0	30	980
10	50	0	50	950
11	60	0	60	900
12	80	0	80	840
13	90	0	90	760
14	110	0	110	670
15	100	0	100	560

16	90	0	90	460
17	80	0	80	370
18	60	0	60	290
19	50	0	50	230
20	30	0	30	180
21	30	0	30	150
22	20	0	20	120
23	0	100	0	100

Total Cooling Load = 900kWh
Ice Bank Capacity = 1000kWh

Figure 6-8: Sample ice bank charging and discharging performance

It can be seen that any cooling done by the chiller during the charging period is simply added to the ice bank's stored cooling potential at the beginning of that hour. Any cooling provided by the ice bank is simply subtracted from the ice bank's stored cooling potential at the beginning of the hour.

There is no account made for ice bank losses. BDP have specified that standing losses from the ice bank are less than 1% of the total stored capacity over 24 hours when in a 30°C environment.

6.4.2 Control

The ice bank used in the model has a number of control options for charging and discharging. The charging options included in the model are: prolonged charge, chiller load dependent charge and ambient air temperature dependent charge. The discharging options included in the model are store priority discharge, chiller priority discharge, constant proportion discharge and level off discharge. These charging and discharging options are discussed in detail in Chapter 10.

The charge rate of the ice bank is determined by the charging option selected by the user and the depletion of the ice bank at the beginning of the charging period. The discharge rate or cooling to be provided by the ice bank is determined externally to the TRSNYS model using Excel. This is done because the cooling loads over the entire discharge period must be known to determine the cooling to be provided by the ice bank at each timestep. The cooling to be provided by the ice bank for each discharge control and at each timestep is calculated by Excel and input to the TRNSYS model. The TRNSYS ice bank model can then select which discharge rate to use, according to the discharge option selected by the user.

The ice bank is also controlled by its availability setting in the simulation settings.

7 NGI Load Determination

This chapter describes the process used to determine the NGI loads to be used in the developed model. Figure 7-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

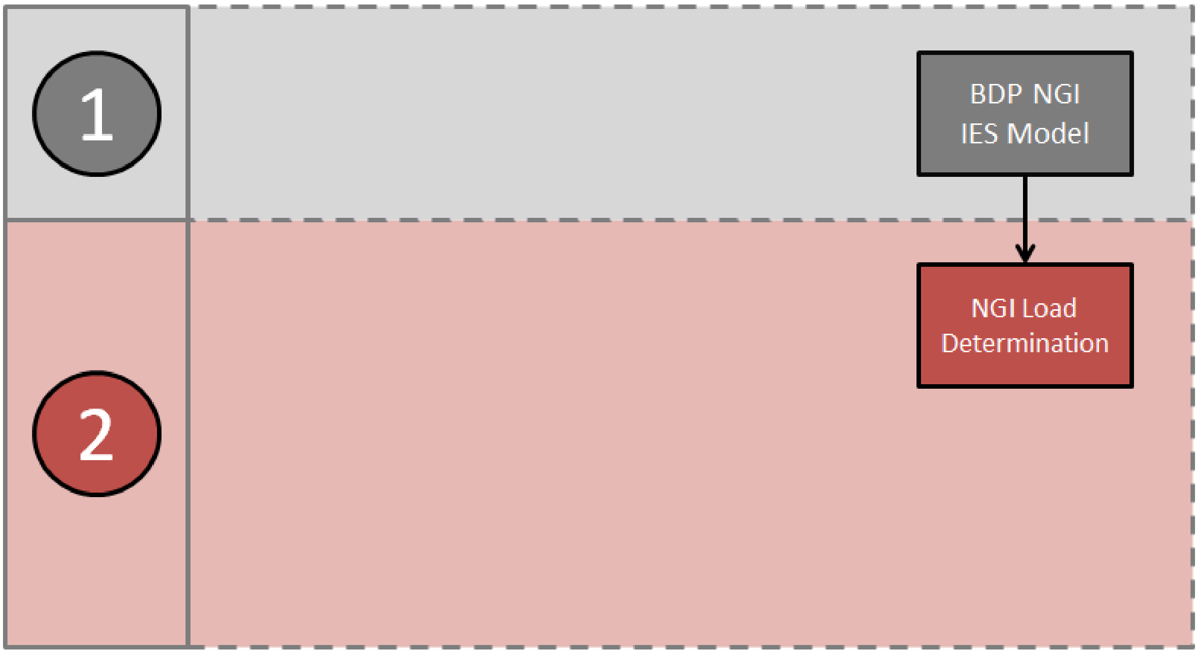


Figure 7-1: Chapter 7 process diagram tasks

7.1 Introduction

The NGI loads required for the developed model were the annual NGI heating, cooling and electrical loads. The IES model provided by BDP was used to determine these annual loads at timesteps of one hour. Only loads from zones which were to be served by the NGI's newly refurbished systems were used. The selected loads from the relevant wings of the NGI model were exported to Excel. The loads were analysed and compared against existing NGI load data when possible. If necessary, the loads were manipulated to represent the actual NGI loads.

The following subsections explain how each of the loads were estimated using data from the IES model. The final annual loads input used for the developed model are also provided in graph form. Area graphs are used to show both the kW and kWh values of the loads.

7.2 NGI Heating Loads

The NGI heating load is divided into a higher temperature and lower temperature heating load. The LTHW flow and return temperatures required by each load are given in Table 7-1.

Table 7-1: NGI LTHW flow and return temperatures

Load	LTHW Flow Temperature (°C)	LTHW Return Temperature (°C)
Higher Temperature Heating Load	82	71
Lower Temperature Heating Load	40	35

The lower temperature heating load consists of the sculpture garden's underfloor heating load and the Dargan and Milltown air handling unit's (AHU) heat recovery coil loads. The Dargan and Milltown AHUs serve the Dargan and Milltown multizone air with reheat systems respectively. The schematics for these air systems are provided in the Appendix A1. The heating that is provided by the Dargan and Milltown heat recovery coils depends on the heating and cooling loads within each of the respective zones. If any of the zones require cooling, the heating load that can be provided by that zone's AHU heat recovery coil is limited to the heating required to preheat the AHU's incoming fresh air. Even if no zones require cooling, the heating that can be provided by the heat recovery coils is still limited by the supply air temperature required for the zone with the smallest heating load. Unfortunately the IES model did not include a detailed HVAC system so the coil loads had to be estimated.

The lower temperature heating load used for the model consisted of the sculpture garden's underfloor heating load and the AHU heat recovery coils load adjusted for the respective zone's heating and cooling loads. The total heating load from the NGI IES model was used to determine the total NGI heating load. The higher temperature heating load was determined by simply subtracting the lower temperature heating load from the total heating load.

The heating load used from the IES model made no account for the reheat loads, overcooling of the supply air or reheat inefficiencies. Reheat loads are present whenever there is dehumidification required. An additional heating load equal to 30% of any dehumidification load was added to the total heating load to account for this. The total heating load was increased by a further 20% to ensure that the IES model did not underestimate the heating load. A minimum total heat load of 150kW was applied throughout the year. This minimum total heat load corresponds to the actual known heating base load for the NGI. Whenever this limit was applied during the year, the reheat loads associated with the dehumidification loads were still added to the base load of 150kW.

The NGI's annual gas consumption for the years 2008 to 2011 were provided by BDP. The gas consumption corresponds to the gas required by the boilers to meet the NGI heating load. These fuel profiles were used to validate the heating load used for the model. The annual gas consumption profile that would be consumed if boilers of 91% efficiency provided the entire estimated NGI heating load was determined. The existing and resulting estimated annual fuel profiles were then compared as shown in Figure 7-2.

It can be seen that the fuel profile trends are similar in both the existing and estimated annual fuel profiles. The gas consumed reached a maximum during the winter months and a minimum during the summer months. However, the estimated fuel profile was much greater than the existing fuel profile at all times during the year except for the summer months. The fuel profiles for the summer months were similar as the actual NGI base heating load of 150kW was applied in the estimated loads.

However, the difference between the fuel profiles for the remainder of the year indicated that the additional percentages used to estimate the total heating loads needed revision.

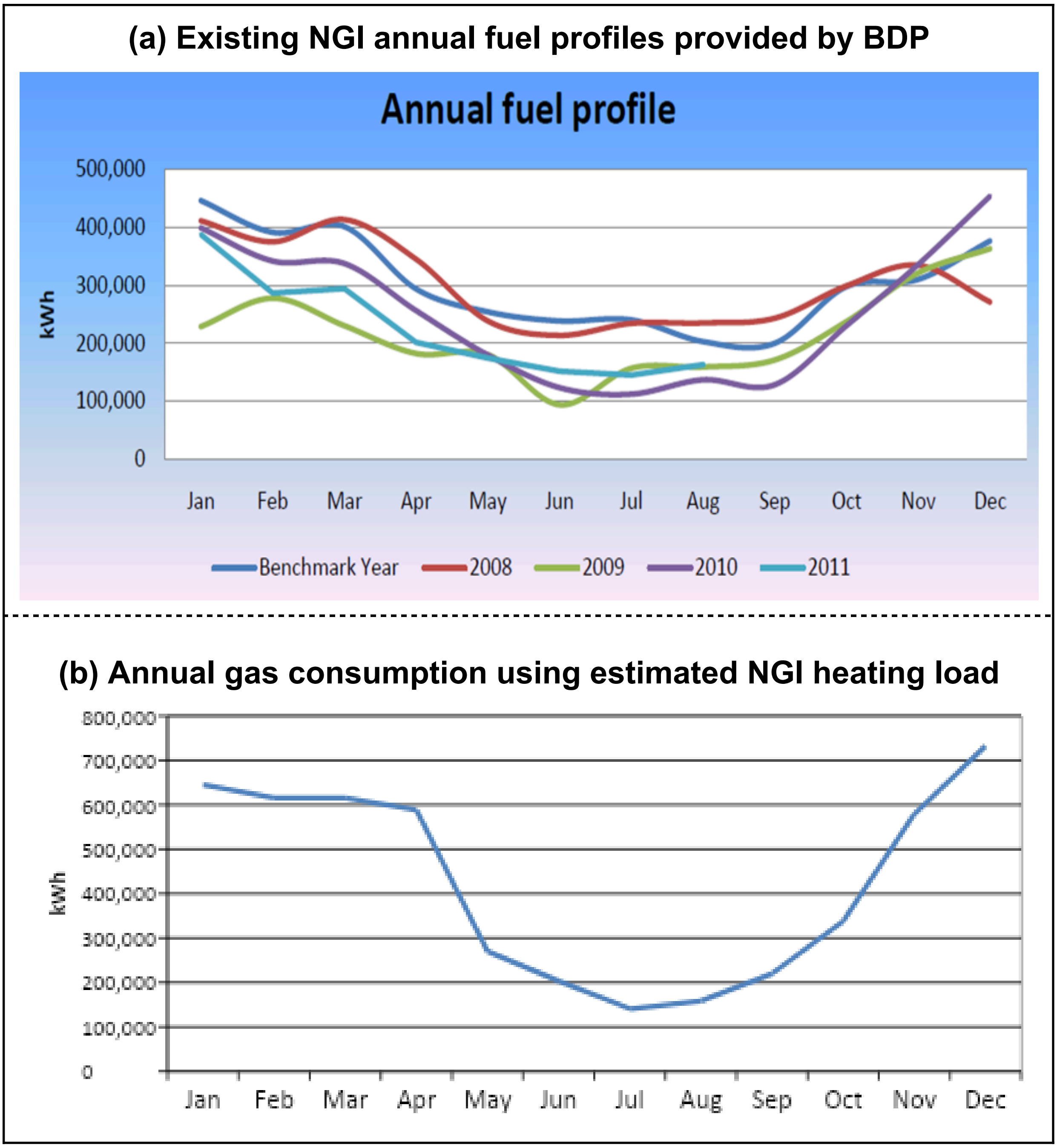
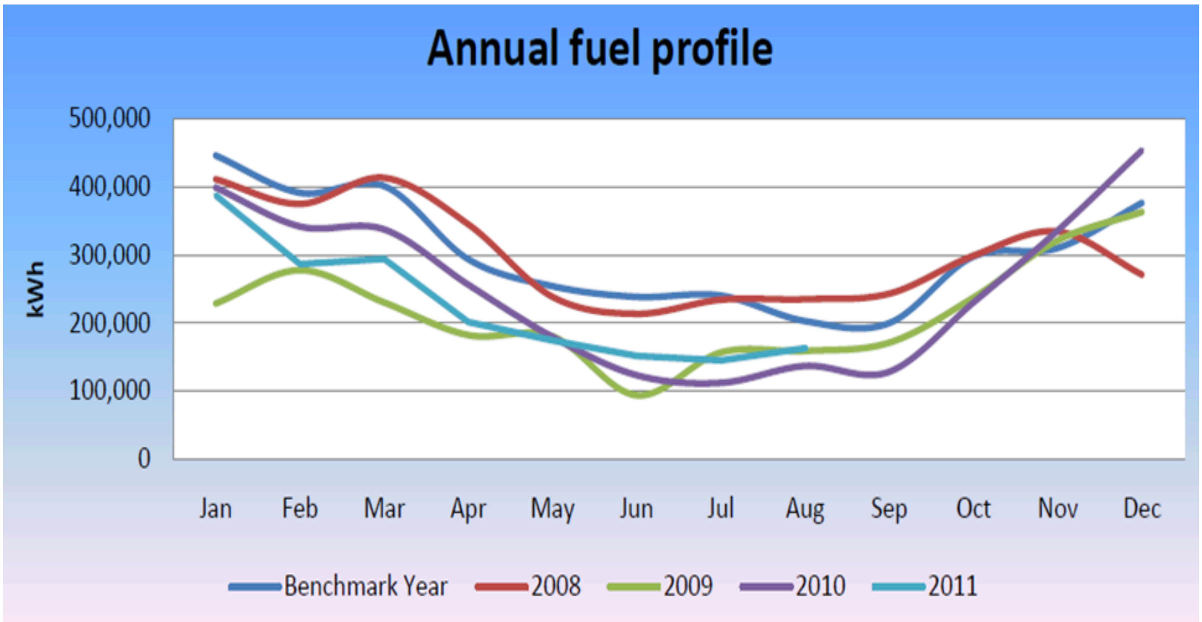


Figure 7-2: NGI annual fuel profiles - (a) existing and (b) estimated

The estimated annual fuel profile should be slightly higher than the existing annual fuel profiles due to the additional reheat loads required. The percentage adjustment used for the estimated annual profile was altered until it was slightly higher than the existing annual fuel profiles. The final percentage adjustment used was to reduce the total IES heating load by 20%. The resulting annual fuel profile was compared against the existing annual fuel profile as shown in Figure 7-3.

It can be seen that the estimated annual fuel profile was only slightly higher than the existing annual fuel profiles throughout the year. Therefore the estimated heating loads were appropriate. The actual NGI annual fuel profile determined by the model would be different as the low energy plant items would be used as well as the boilers. However, the annual heating loads input to the model would be correct.

(a) Existing NGI annual fuel profiles provided by BDP



(b) Annual gas consumption using revised estimated NGI heating load

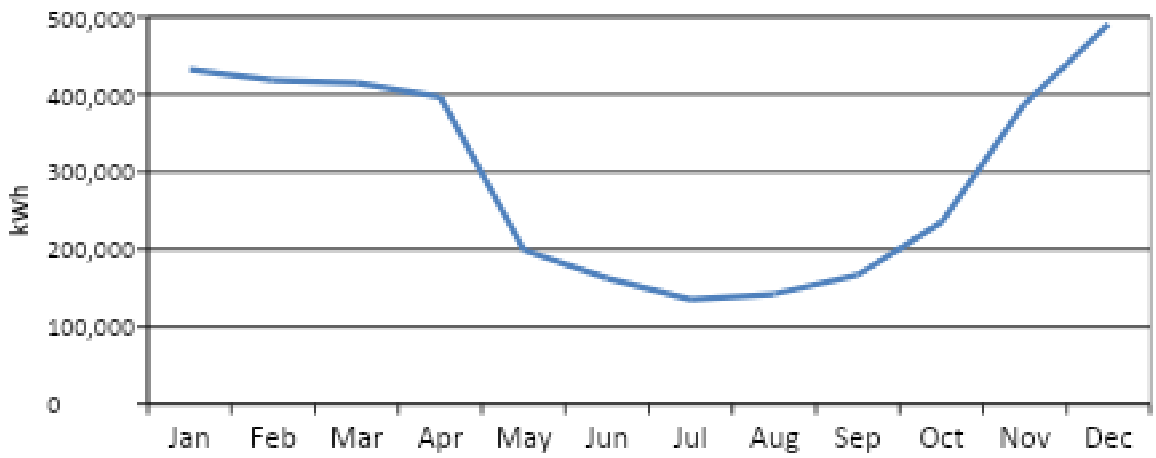


Figure 7-3: NGI annual fuel profiles - (a) existing and (b) estimated (revised)

The final annual heating loads used for the model are shown in Figure 7-4. The annual lower temperature heating load makes up approximately 30% of the total annual heating load. The peak total heating load is approximately 1000kW.

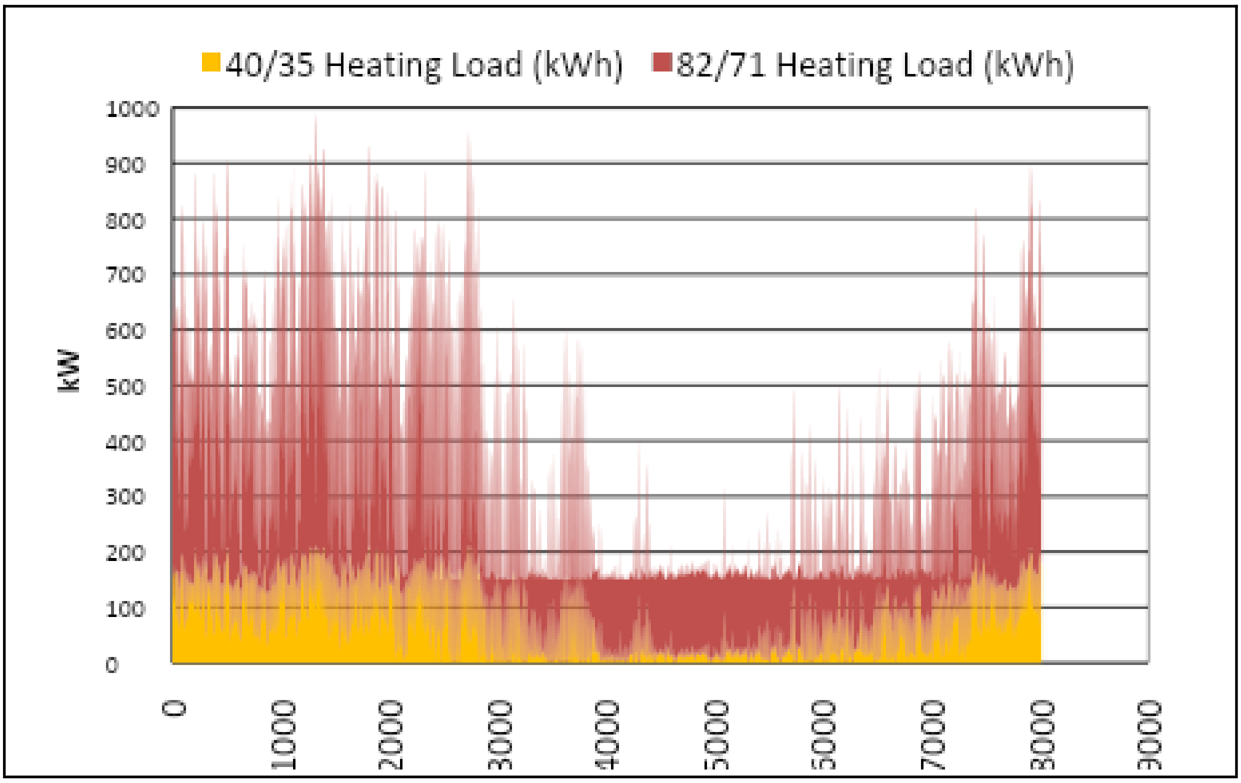


Figure 7-4: Annual NGI heating loads

7.3 NGI Cooling Loads

The NGI cooling load used for the developed model included the sensible and latent cooling loads for the Dargan, Milltown and Biet wings only. It is possible to transfer some cooling to the Millennium wing but this is an added bonus and not accounted for in the finalised load data.

The CHW flow and return temperatures used depend on the operation of the ice bank. Each of the temperatures used are capable of providing both the sensible and latent cooling loads. For this reason, the NGI sensible and cooling loads were combined into a total cooling load within the model. The CHW temperatures used by the cooling system are shown in Table 7-2.

Table 7-2: NGI CHW flow and return temperatures

Ice Bank Operation	CHW Flow Temperature (°C)	CHW Return Temperature (°C)
Standby	6	12
Charging	-6	-2
Discharging	3	9

The sensible and dehumidification cooling loads for the Dargan, Milltown and Biet wings were taken from the IES model and summed together to give the total cooling load. An additional 20% was added to this total cooling load to ensure the IES model didn't underestimate the load.

Unlike the heating load, the cooling load was not validated against existing data. However, the cooling load used did account for a known 37kW base sensible cooling load. This load consists of 20kW for a basement comms room, 10kW for a basement security room and 7kW for the remainder of the basement. The resulting annual cooling load used for the model is shown in Figure 7-5.

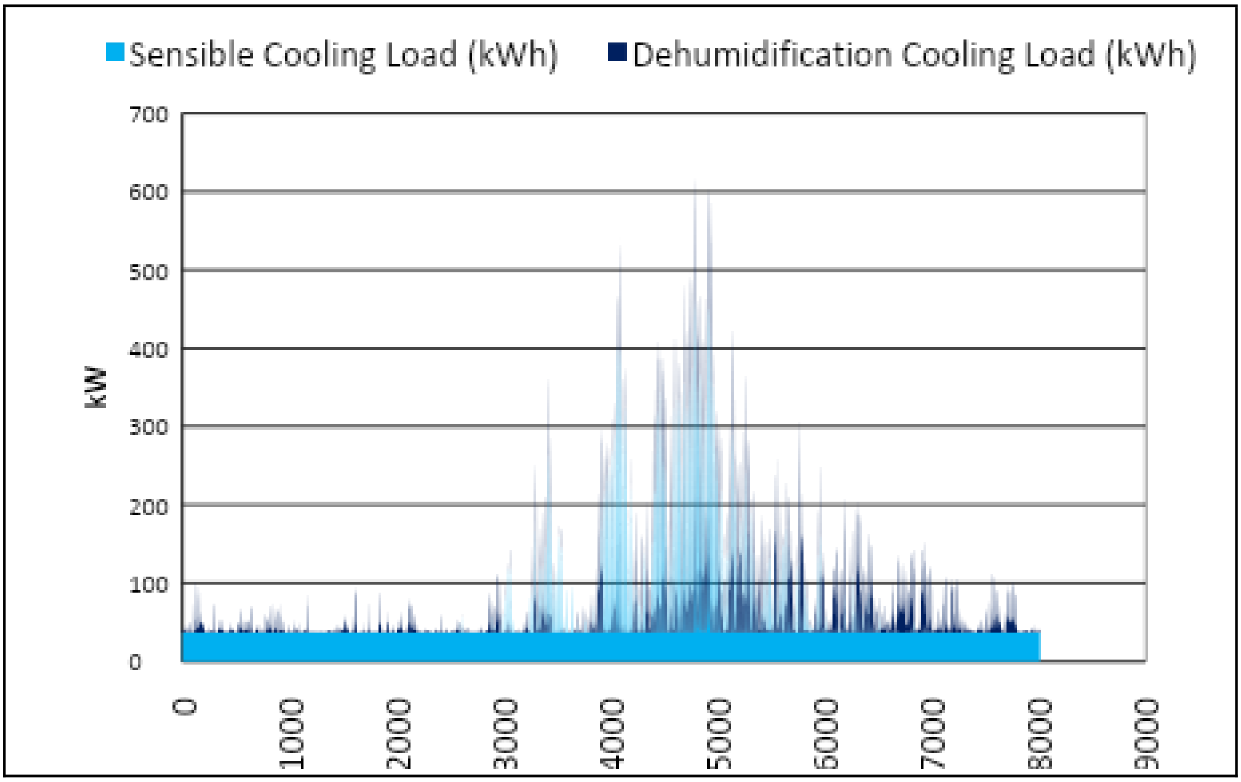


Figure 7-5: Annual NGI cooling loads

It can be seen from Figure 7-5 that the base sensible cooling load is applied throughout the winter and mid seasons. This base sensible cooling load is occasionally added to by dehumidification loads. During the summer months, the total cooling load increases dramatically as the sensible and dehumidification loads both increase. The peak total cooling load for the Dargan, Milltown and Biet wings is approximately 600kW.

7.4 NGI Electrical Loads

The CHP unit used in the NGI can provide electricity to the entire NGI building by simply connecting to the main distribution board. For this reason the IES electrical load for the entire NGI building was used. However, only the lighting electricity and small electrical loads were taken from the IES model. The system electrical load from the IES model was omitted as it becomes obsolete once the TRNSYS model alters the NGI system. The IES model used a simple electrical lighting and small electrical load profile. This load profile changed the electrical loads according to the day of the week and the hour of the day.

The NGI electrical load used for the TRNSYS model consisted of the IES lighting and small electrical loads and a known continuous electrical base load of 150kW. The annual NGI electrical loads used in the model are shown in Figure 7-6.

It can be seen that the NGI electrical load has a constant base load equal to the applied base load of 150kW. It rises to approximately 300kW each day and drops to the base load each night and weekend.

The annual electricity profile was not validated even though an existing annual electricity load profile was available. It was possible to validate the annual heating load from existing data for a number of reasons. A relatively accurate estimation of the heating load could be made as the IES model accounts for the thermal performance of the building. This heating load could also be compared against the existing data by making a relatively safe assumption that boilers with an efficiency of 91% provided the heating for the NGI building in the existing profiles. The annual fuel profile could effectively be reverse engineered to determine the heating loads in the NGI.

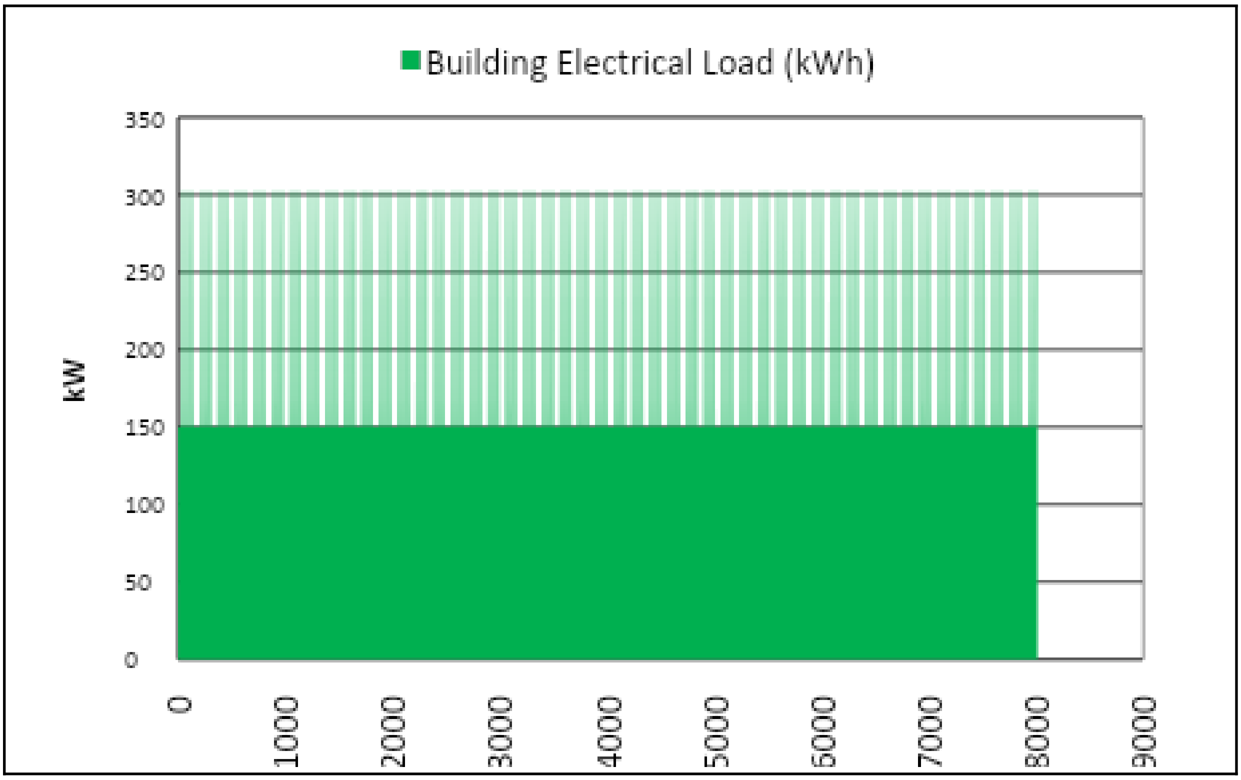


Figure 7-6: Annual NGI building electrical loads

A similar approach could not be used to reverse engineer the existing annual electricity profile. Too many assumptions would have to be made about each of the electrical loads present in the NGI to determine what electrical loads should be maintained. The resulting annual electricity load profile would also be somewhat irrelevant as the electrical lighting and HVAC systems of the NGI are to be changed as part of the refurbishment. It is also less important to accurately predict the NGI electrical load as it does not affect the performance of the low energy plant items. The only affect the electrical load may have is on the CHP unit. If the electrical load is too low, the CHP unit would have to reduce its power output so that the electrical load is not exceeded. However, the CHP unit was sized according to the base electrical load of 150kW so this never occurs in the model.

A disadvantage of not accurately predicting the electrical load is that the model cannot determine if the NGI's MIC is exceeded. This feature would be particularly useful for determining the optimum ice bank discharge control option. However, the relative advantages of each option can still be determined.

8 TRNSYS Model

This chapter describes the TRNSYS model developed for the evaluation and optimisation of the NGI alternative plant items. Figure 8-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

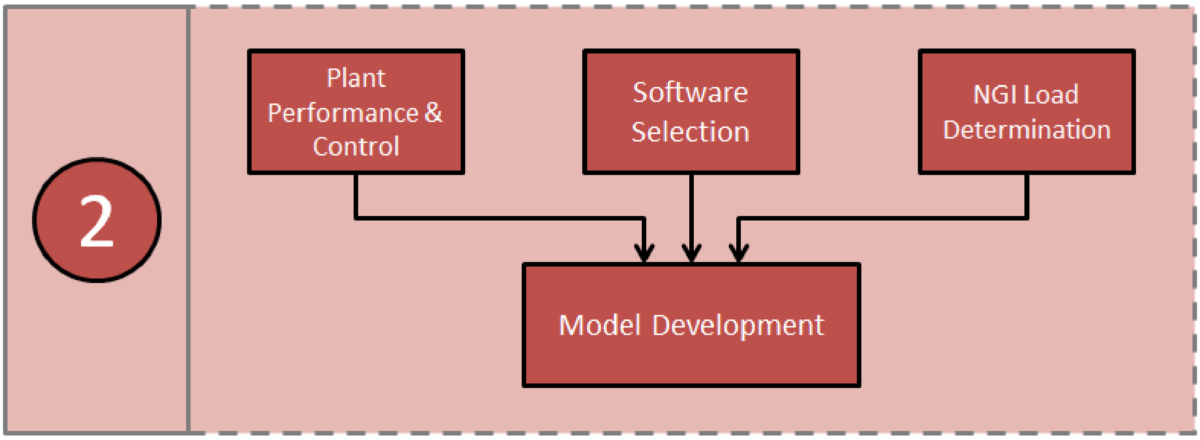


Figure 8-1: Chapter 8 process diagram tasks

8.1 Introduction

The developed TRNSYS model may be simplified into four main components:

1. NGI Load Data
2. User Input
3. Simulation Engine
4. Data Output

Figure 8-2 shows the four components of the simplified TRNSYS model. The NGI load data is input to the simulation engine via a text file. The user inputs the plant and simulation options to be used for the current simulation. The simulation engine takes the NGI load data and user inputs and determines the required simulation outputs. The data is then exported from the simulation engine via another text file. The four main model components are discussed in the following subsections.

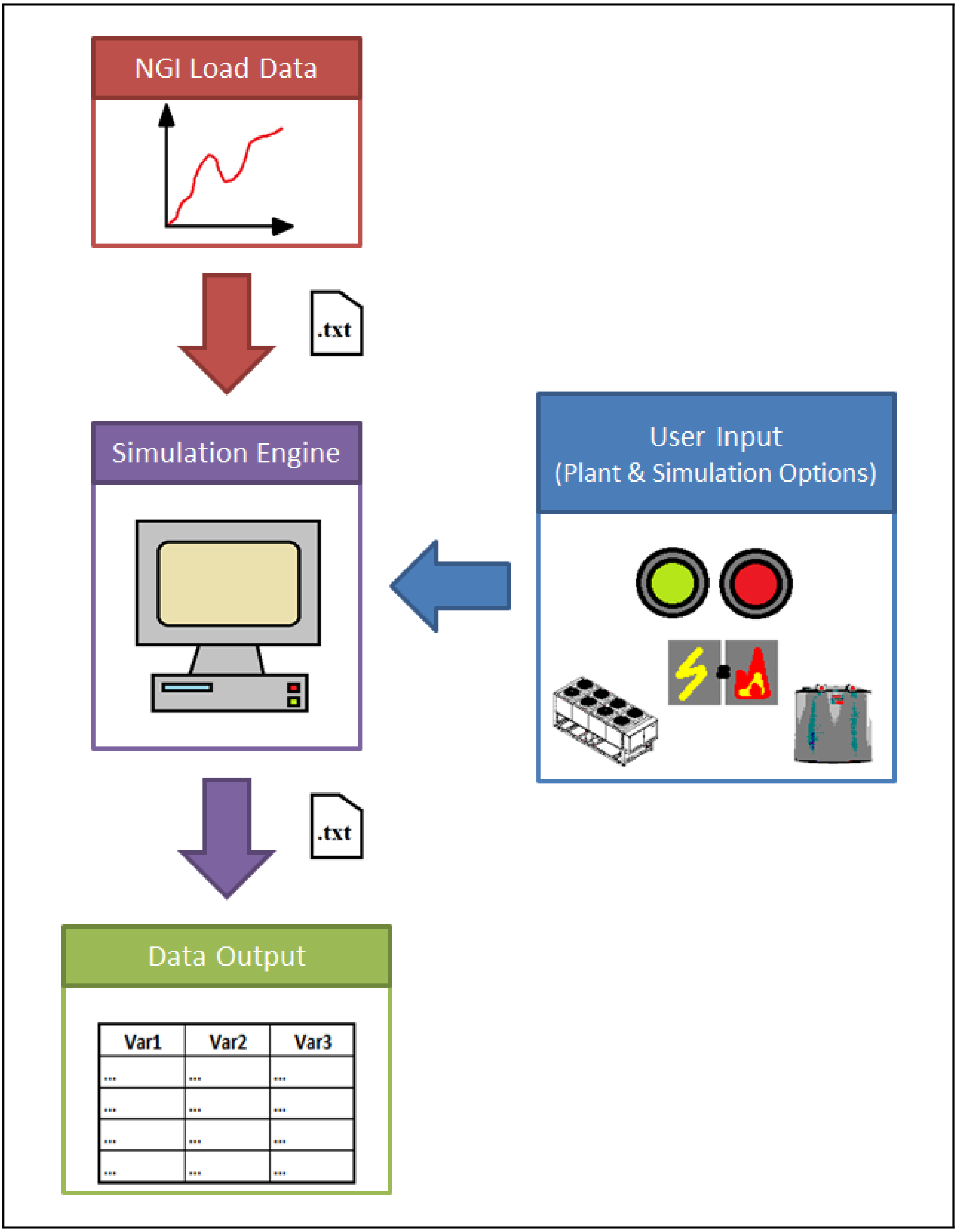


Figure 8-2: Simplified TRNSYS model

8.2 NGI Load Data

The initial step in the TRNSYS model is to determine the NGI Loads to be used for the simulation. These loads must be input as a text file to the simulation engine. A combination of IES and Excel were used to determine the NGI loads as described in Chapter 7. The finalised NGI loads were exported from Excel as a text file. This text file is available in Appendix C3.

The text file contained 8760 rows of data corresponding to each hour of the year. The following loads were included in the text file:

- annual higher temperature heating load
- annual lower temperature heating load
- annual total cooling load
- annual building electrical load

The two NGI heating loads were included in the text file individually as the simulation engine had to be able to distinguish between the loads. Once the loads had been input to the simulation engine, the hourly data could be interpolated to produce data at whatever timestep required.

The annual heating loads input to the TRNSYS model made up the total heating to be provided by the NGI systems. However, the total cooling load and building electrical load were not necessarily the total cooling and electrical loads to be met by the NGI systems. The ice bank charging load and chiller electrical load are added to the total cooling load and building electrical load respectively when present within the TRNSYS model.

8.3 User Input

The second step in the TRNSYS model is to set the required plant and simulation options to be used in the simulation. This information is entered within the TRNSYS model's simulation studio. The simulation studio within TRNSYS was briefly described in section 5.6. It consists of a series of components linked together to represent a system. Each component represents a plant item or control feature and has a number of parameters and inputs that can be altered by the user. However, it can be tricky to find the required parameter or input to change and even trickier to change it without disrupting the simulation engine.

For this reason, a *Model Options* component was created within the simulation studio. This component contains the majority of the plant and simulation options and allows the user to easily change them without disrupting the simulation engine. Table 8-1 shows a sample number of the model options and explains how the user may alter them. Simple Boolean or integer values are used to distinguish between various simulation and plant control options.

The plant control options which may be selected by the user are described in detail in Chapter 6. The simulations options that can be selected by the user include:

- The availability and scheduled maintenance periods of each plant item.
- The gas and grid electricity cost and CO_2 intensity profiles. These may be kept constant or altered according to the time of day.
- The start and end time of the simulation in hours. A start time of 0 indicates the simulation starts at 00:00 on the 1st of January. An end time of 8760 indicates that the simulation ends at 00:00 on the 1st of January of the following year. Different months and simulation lengths may be selected by inputting the corresponding start and end times. The simulation run time is only limited by the available NGI load data.

Table 8-1: Sample simulation studio user interface

Sample of the *Model Option* component's User Interface

		Name	Value
10		CHP_Available	○ 0 ◉ 1
11		IB_Available	○ 0 ◉ 1
12		CHP_Qpriority_night	○ 0 ◉ 1
13		IB_Control_Charge	1
14		IB_Control_Discharge	2
15		Chiller_Heating_NightOnly	○ 0 ◉ 1

Variable Name	Description & *Options*
CHP_Available	Whether the CHP unit is available during the simulation *1 = Available* *0 = Unavailable*
IB_Available	Whether the Ice Bank is available during the simulation *1 = Available* *0 = Unavailable*
CHP_Qpriority_night	Whether the CHP heat should be given priority over the chiller heat during the night. There is similar option for during the day. *1 = CHP unit Heat Priority* *0 = Chiller Heat Priority*
IB_Control_Charge	The Ice Bank charge control option to be used during the simulation. *Integer values from 1 to 3 correspond to particular ice bank charge control options.*
IB_Control_Discharge	The Ice Bank discharge control option to be used during the simulation. *Integer values from 1 to 4 correspond to particular ice bank discharge control options.*
Chiller_Heating_NightOnly	Whether the ASHP feature of the chiller should only be used during off peak electrical hours. *1 = Only off peak operation* *0 = Anytime operation*

8.4 Simulation Engine

The third step in the TRNSYS model is to run the simulation engine. This simulation engine takes the parameters and inputs from each component and determines each component's outputs from the mathematical equations defined in each component's source code. The simulation engine carries out this process at each timestep and may have to do a number of iterations before converging on a solution. Iterative calculations are required as the outputs of one component may affect the inputs of another component which in turn affect the inputs for the first component. An error message is provided if the simulation engine cannot converge on a solution. This iterative convergence process is graphically represented in Figure 8-3.

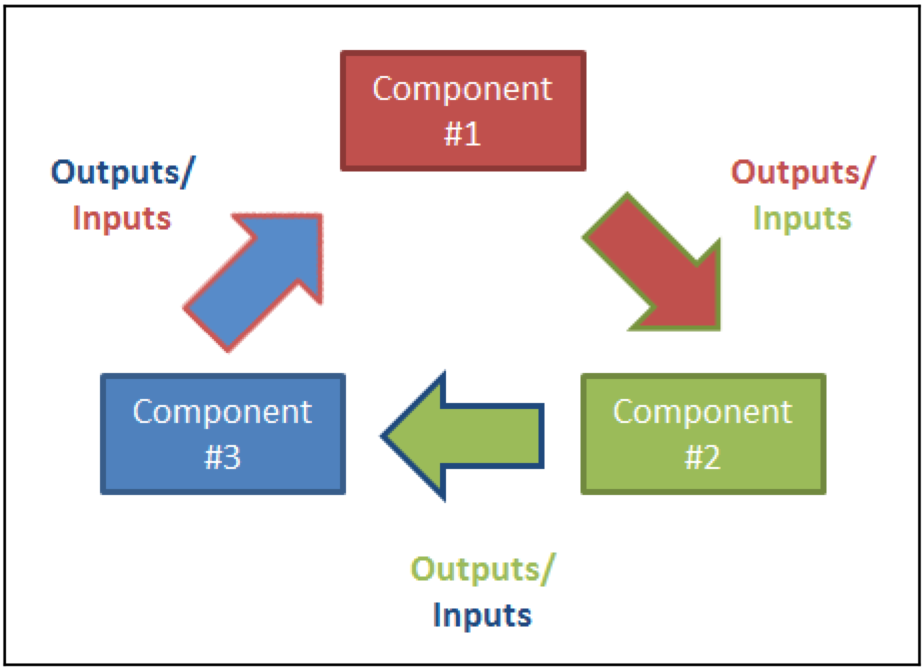


Figure 8-3: Simulation engine iterative convergence process

The TRNSYS simulation studio allows *Proformas* of new components to be created. These Proformas determine how a component appears in the simulation studio and the number of variables assigned to that component. Once a Proforma has been created for a new component, a skeletal source code can be exported to the user's IDE. This skeletal source contains information vital to the running of the simulation engine such as the number of variables and how the component should be handled in iterative processes. The source code for the manipulation of the component's variables to determine the component's outputs must be added by the user. The completed source code must then be complied into a DLL for use by the simulation engine.

Components were created for each of the low energy plant items and for various control purposes. The performance of each plant item, as described in Chapter 6, was incorporated into each plant item component's source code. The Proformas and DLLs for each component created are available in Appendix C1 and Appendix C2 respectively.

The components used in the simulation engine were created and connected together in a particular structure. This structure was designed to replicate how the NGI systems actually operate. The structure consisted of four processes:

1. The process to provide the higher temperature heating load
2. The process to provide the lower temperature heating load
3. The process to provide the total cooling load and ice bank charging load
4. The process to provide the building electrical load and chiller electrical load

Each of these processes is described in turn in the following subsections. The structure used is graphically represented in Figure 8-4. The heating and cooling systems of the NGI building use variable volume constant temperature fluids to distribute their respective loads. Therefore the mass flow rates (MFR) of the LTHW and CHW systems are adjusted and the respective flow and return temperatures remain constant. The LTHW and CHW temperatures used are shown in Table 7-1 and Table 7-2.

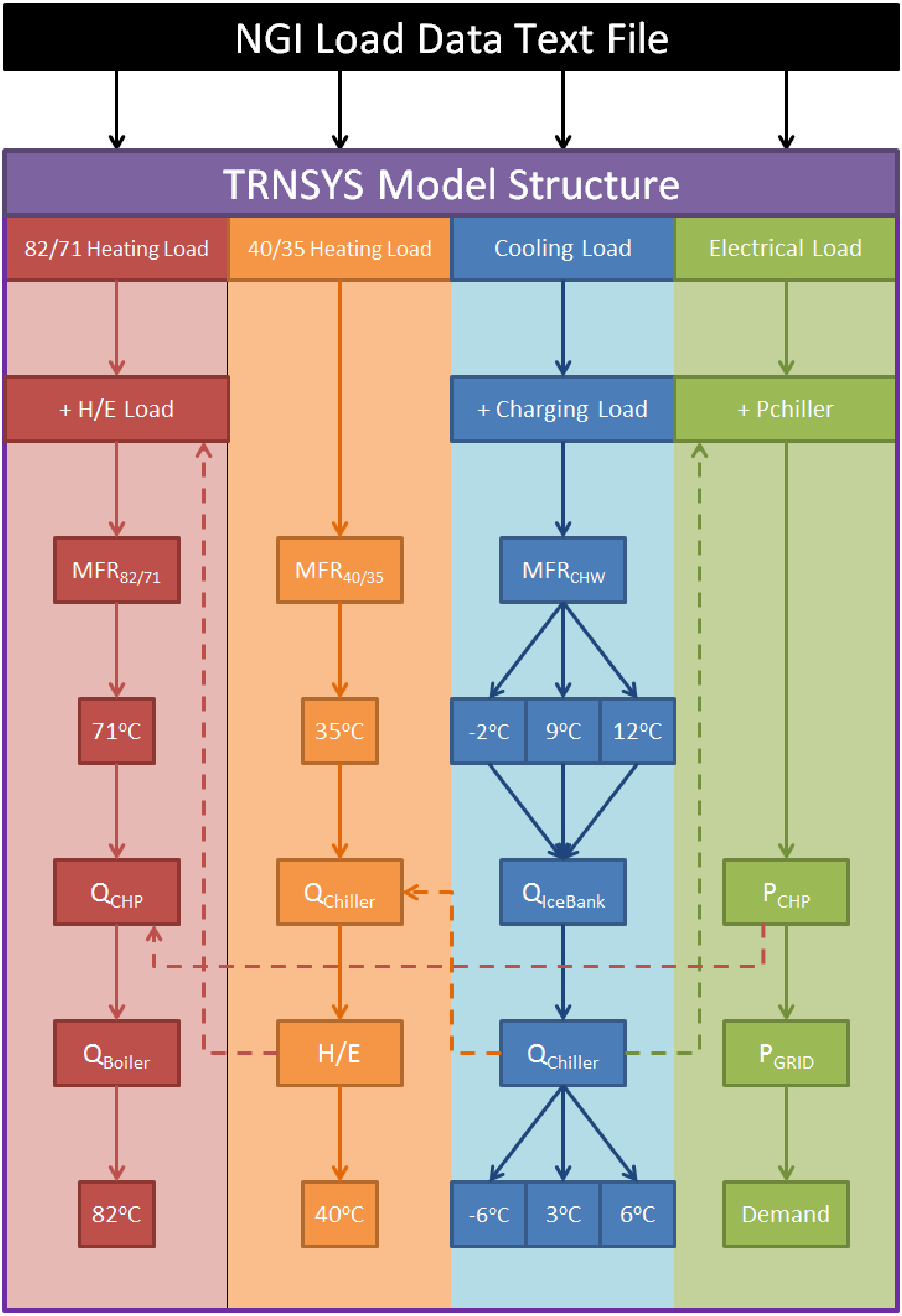


Figure 8-4: TRNSYS Model Structure

8.4.1 Process 1: Higher Temperature Heating Load

The higher temperature heating load process is represented in red under the *TRNSYS Model Structure* in Figure 8-4. The higher temperature heating load is supplied at LTHW flow and return temperatures of 82°C and 71°C respectively. The NGI heating system uses a heat exchanger between the higher temperature and lower temperature LTHW fluids to enable heat to be transferred between the fluids. Higher temperature heating sources are used to provide the lower temperature heating load if the lower temperature heating sources cannot reach the required LTHW flow temperature.

The higher temperature heating load is input from the NGI load data text file and is labelled as "*82/71 Heating Load*" in Figure 8-4. The heat exchanger load, labelled "*+ H/E Load*", may or may not be present. The MFR of the LTHW is adjusted according to the combined higher temperature heating load and heat exchanger load present. The higher temperature heating sources available are the CHP unit and the boilers. Return LTHW at a temperature of 71°C is first heated by the CHP unit. The amount of heat provided by the CHP unit depends on the current power output of the unit. The boilers are used when necessary to raise the CHP unit's exiting LTHW temperature to 82°C.

8.4.2 Process 2: Lower Temperature Heating Load

The lower temperature heating load is represented in orange under the *TRNSYS Model Structure* in Figure 8-4. The lower temperature heating load is supplied at LTHW flow and return temperatures of 40°C and 35°C respectively.

The lower temperature heating load is input from the NGI load data text file and is labelled as "*40/35 Heating Load*" in Figure 8-4. The MFR of the LTHW is adjusted according to the lower temperature heating load present. The lower temperature heating load sources available are the chiller and the heat exchanger. Return LTHW at a temperature of 35°C is first heated by the chiller. The heat output of the chiller depends on the recovered heat provided by the chiller's cooling process and the enabled operating modes. The use of the chiller as an ASHP is discussed further in Chapter 11. Any additional heating required to raise the LTHW temperature to 40°C is provided by the heat exchanger.

8.4.3 Process 3: Total Cooling Load & Ice Bank Charging Load

The total cooling load and ice bank charging load process is represented in blue under the *TRNSYS Model Structure* in Figure 8-4. The CHW flow and return temperatures used depend on the operation of the ice bank. The flow and return CHW temperatures shown in Figure 8-4 represent the flow and return CHW temperatures for charging the ice bank, discharging the ice bank and not using the ice bank respectively.

The total cooling load is input from the NGI load data text file and is labelled as "*Cooling Load*" in Figure 8-4. The ice bank charging load, labelled "+ *Charging Load*", may or may not be present, depending on whether the ice bank is being charged or not. The MFR of the CHW is adjusted according to the combined total cooling load and charging load present. The CHW cooling sources available are the ice bank and the chiller. The CHW load to be provided by the ice bank depends on the discharging control option selected. The ice bank discharging control options are discussed in detail in Chapter 10. Any CHW load not provided by the ice bank is provided by the chiller so that the required CHW flow temperature is reached.

8.4.4 Process 4: Building Electrical and Chiller Electrical Loads

The total building electrical load and chiller electrical load process is represented in green under the *TRNSYS Model Structure* in Figure 8-4. The building electrical load is input from the NGI load data text file and is labelled as "*Electrical Load* ". The chiller electrical load, labelled "+ *Pchiller*", may or may not be present, depending on whether the chiller is operating or not. The combined building electrical and chiller electrical load is first provided by the CHP unit. Electricity is imported from the grid if the power output of the CHP unit is not sufficient to fully meet the electrical demand.

8.5 Data Output

The final step in the TRNSYS model is to output the simulation results. Any variable within the TRNSYS model may be analysed. The simulation studio within TRNSYS allows variables to be tracked in real time as the simulation progresses by using *Online Plotters*. These Online Plotters can plot any variable against time and are great troubleshooting tools. However, for data analysis, it is more useful to have the data available in spreadsheet format.

A *System Printer* is also available in the simulation studio. This System Printer outputs the selected variables at each timestep into a text file. The text file can then be opened in Excel for data analysis purposes. The resulting Excel spreadsheet will include values for each variable at each timestep during the entire simulation. Typical output variables include:

- Low energy plant heating/cooling/electrical outputs
- Low energy plant operating modes and efficiencies
- Wasted energy such as unusable CHP unit heat or chiller recovered heat
- LTHW and CHW temperatures before and after each plant item
- Total gas and grid electricity consumption
- Resulting fuel costs and CO_2 emissions from providing the NGI loads
- Model options used for the simulation

The Excel spreadsheets containing the outputs from each of the simulations run in this thesis are available in Appendix E2.

8.6 TRNSYS Model Use

The TRNSYS model developed may be used to analyse the use of the NGI low energy alternative plant items. As with all models, sensible outputs will only be produced from sensible inputs. The NGI loads used for the TRNSYS model must be representative of the actual loads experienced by the NGI. These can easily be revised by altering the NGI Load Data text file. Most importantly, the modelled performance of the low energy alternative plant items must be representative of the actual performance achieved by these items. The source code of the plant item's component must be altered and recompiled to make a change to its modelled performance. Relevant source code must also be altered and recompiled if additional control features or simulation options wish to be added to the model.

9 Optimum CHP Control Philosophy

This chapter addresses the first thesis objective of determining the optimum CHP unit control philosophy. Figure 9-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

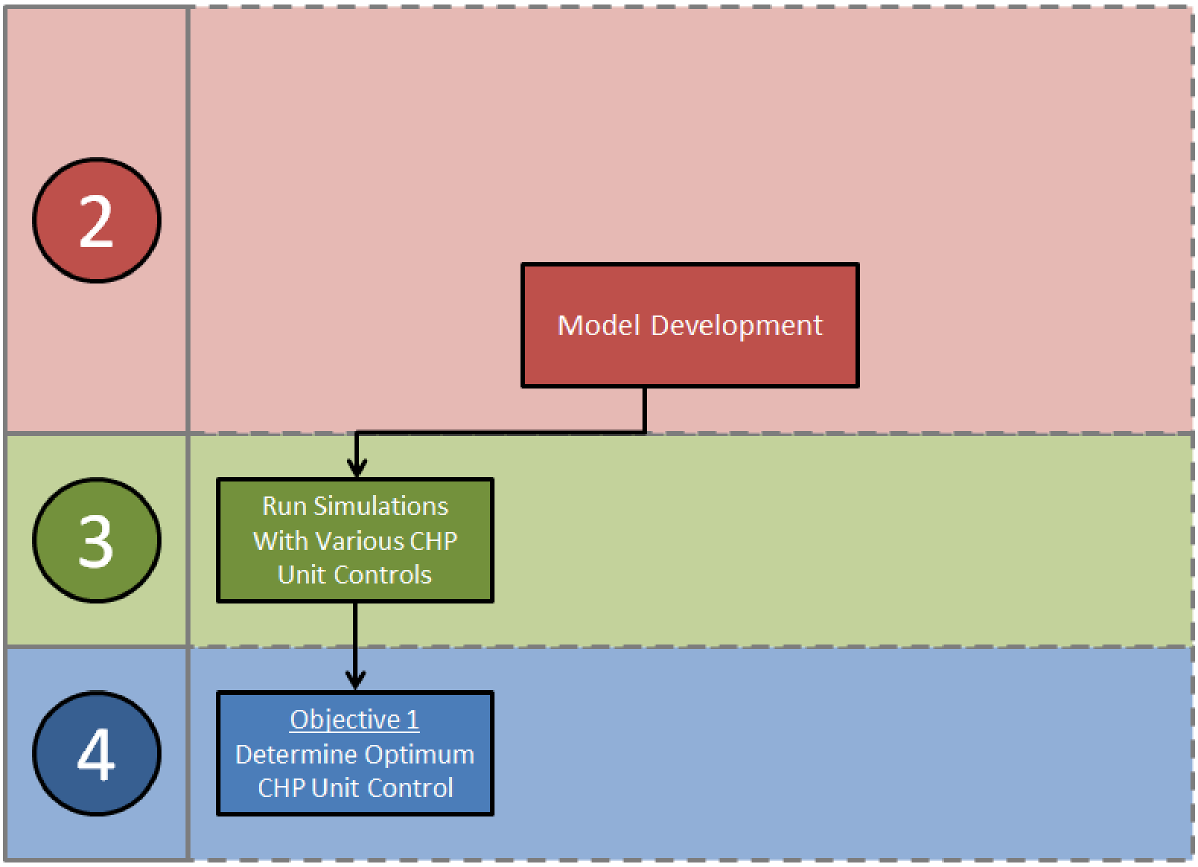


Figure 9-1: Chapter 9 process diagram tasks

9.1 Introduction

The CHP unit generates both electricity and heat for the NGI building. The performance of the CHP unit is determined by the control philosophy used and the available electrical and heating loads of the NGI building. External factors such as the fuel and grid electricity tariffs and CO_2 intensities should also influence when the CHP operates. Two control philosophies were developed for the CHP unit; the first to minimise energy costs and the second to minimise CO_2 emissions.

The overall efficiency or fuel utilisation of a CHP unit is approximately 85%. The overall efficiency or fuel utilisation of a natural gas boiler is approximately 91%. The amount of useful energy output per energy input is therefore greater for a natural gas boiler than for a CHP unit. However, the CHP unit provides both electricity and heat from the same process. Electricity is a higher form of energy than heat and is more expensive and CO_2 intensive as a result. Therefore the energy output of the CHP unit is more valuable than the energy output of the boiler, even though the overall efficiency is lower. Energy cost and CO_2 emission savings from a CHP unit are greatest at higher electrical efficiencies.

The full benefit of the CHP unit is only achieved when both the electrical and heat outputs of the CHP are utilised. The electricity and heating generated by a CHP unit can only be used when there are electrical and heating loads available in the NGI building. If the heating generated by the CHP cannot be used, it must be dumped. If the heating load is relatively low, it may be more beneficial to reduce the power output of the CHP so that all of the generated heat may be used, instead of dumping some of the heat. However, this would result in a drop in electrical efficiency and would require more electricity to be imported from the grid.

9.2 Economic Analysis

An economic analysis was carried out to determine when the CHP unit should operate and what power output it should operate at in order to minimise the NGI's energy costs. The energy cost of providing the NGI electrical and heating loads using a combination of the CHP, boiler and the electricity grid was calculated and compared against a case which only used boilers and the electricity grid.

The energy cost of meeting the NGI building heating and electrical loads depend on the following factors:

- The NGI heating and electrical loads present
- Whether the CHP unit is operating or not
- The performance of the CHP unit and boilers
- The gas and grid electricity tariffs present

Figure 9-2 graphically represents the scenarios investigated for both the economic and CO_2 emission analyses. A constant electrical load of 150kW was used throughout the analyses. Day and night time gas and grid electricity tariffs were used in turn. NGI heating loads ranging from 0kW to 250kW in steps of 50kW were used for each set of tariffs. CHP unit power outputs of 1kWe to 150kWe in steps of 1kWe were used for each NGI heating load.

The energy costs of providing the heating and electrical loads, with and without the CHP unit, were calculated for each combination. When the CHP unit is used, any loads not provided by the CHP unit are provided by boilers and the grid. When the CHP unit is not used, all loads are provided by boilers and the grid.

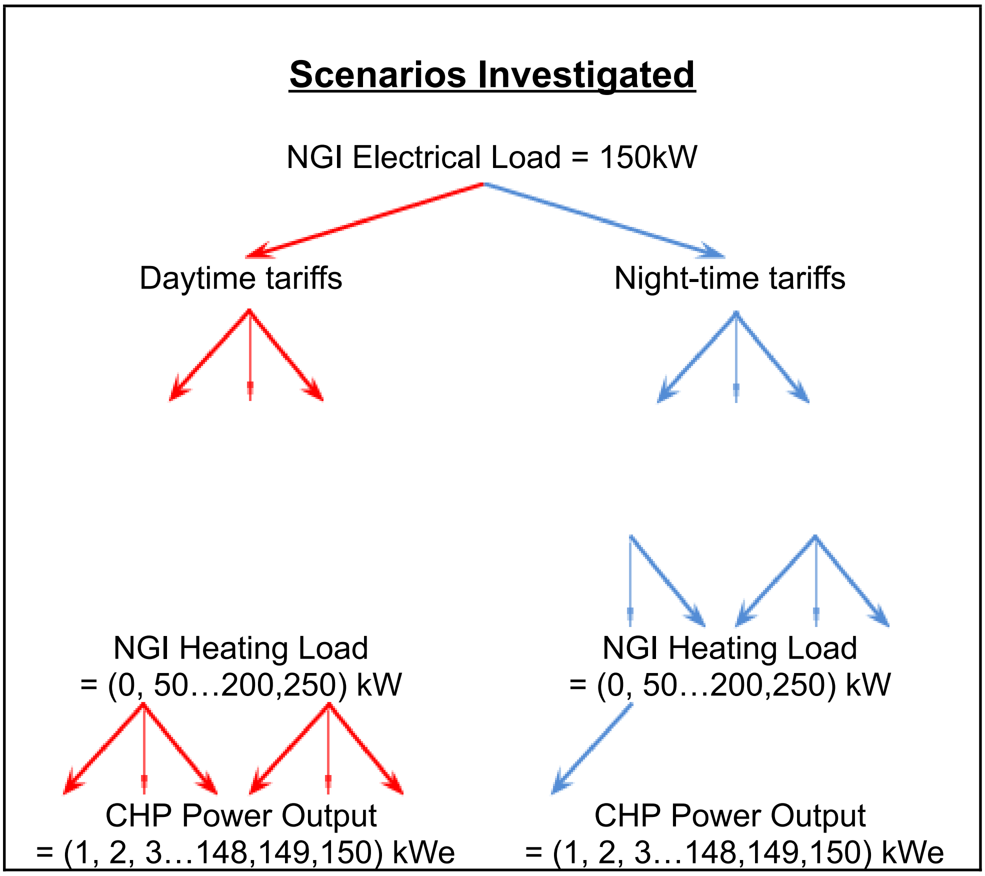
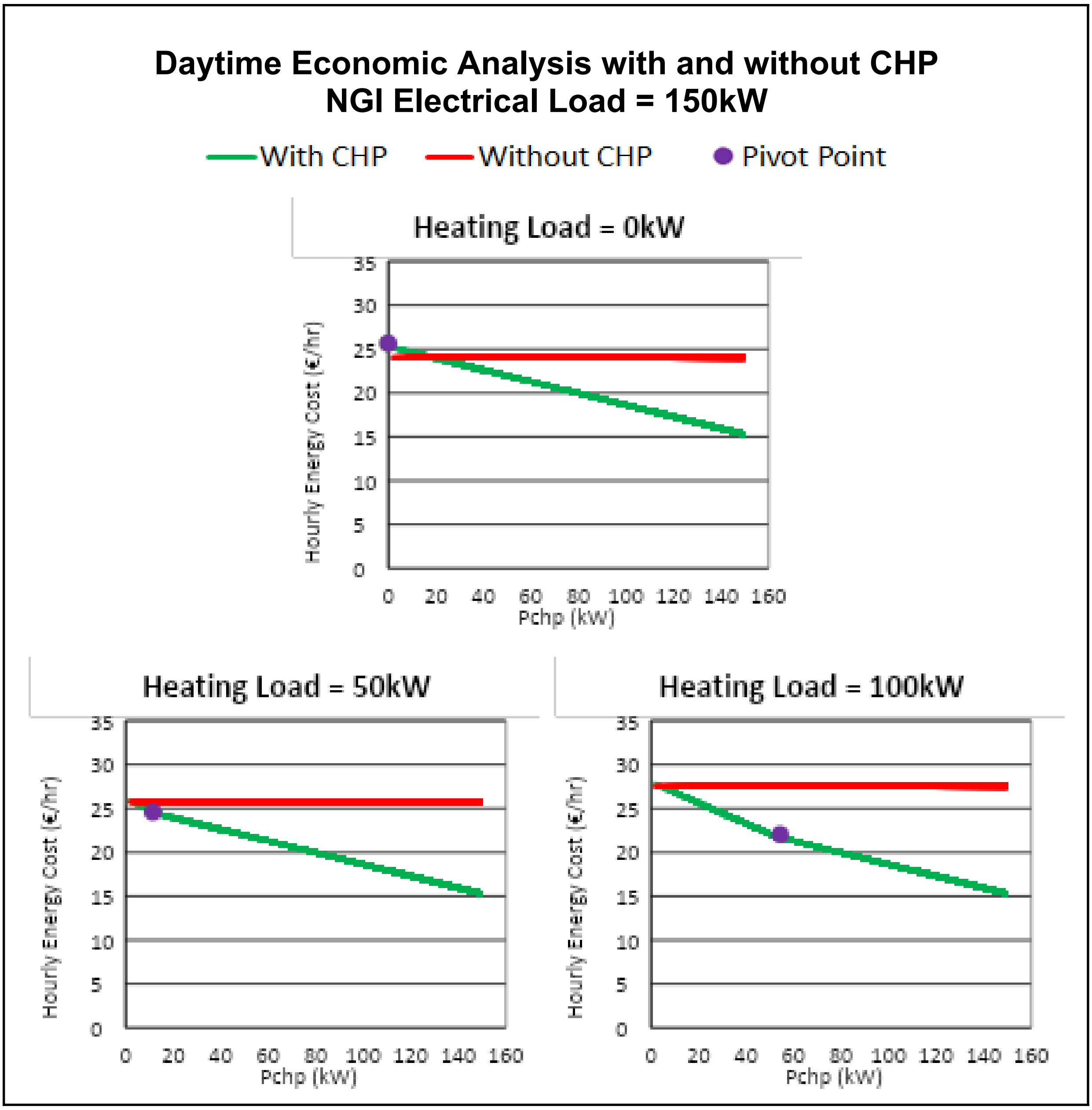


Figure 9-2: Scenarios investigated for CHP economic analysis

Figure 9-3 and Figure 9-4 show the energy costs calculated for the daytime and night time economic analyses respectively. The green lines represent the hourly energy cost when the CHP is used at the given CHP unit power output (labelled *Pchp*) and the remaining loads are provided by the boilers and electricity grid. The purple dot along the green line represents a *pivot point* at which the heat output of the CHP unit matches the heating load exactly. The red line represents the hourly energy cost when the CHP is not used and all of the loads are provided by boilers and the electricity grid. The red line remains constant for each load combination because a change in CHP power output does not affect the CHP as it is not used.

Sections 9.2.1 and 9.2.2 analyse Figure 9-3 and Figure 9-4 respectively.


Daytime Economic Analysis with and without CHP
NGI Electrical Load = 150kW
With CHP
Without CHP
Pivot Point
Heating Load = 0kW
Heating Load = 50kW
Heating Load = 100kW
Hourly Energy Cost (€/hr)
Pchp (kW)
0 5 10 15 20 25 30 35
0 20 40 60 80 100 120 140 160

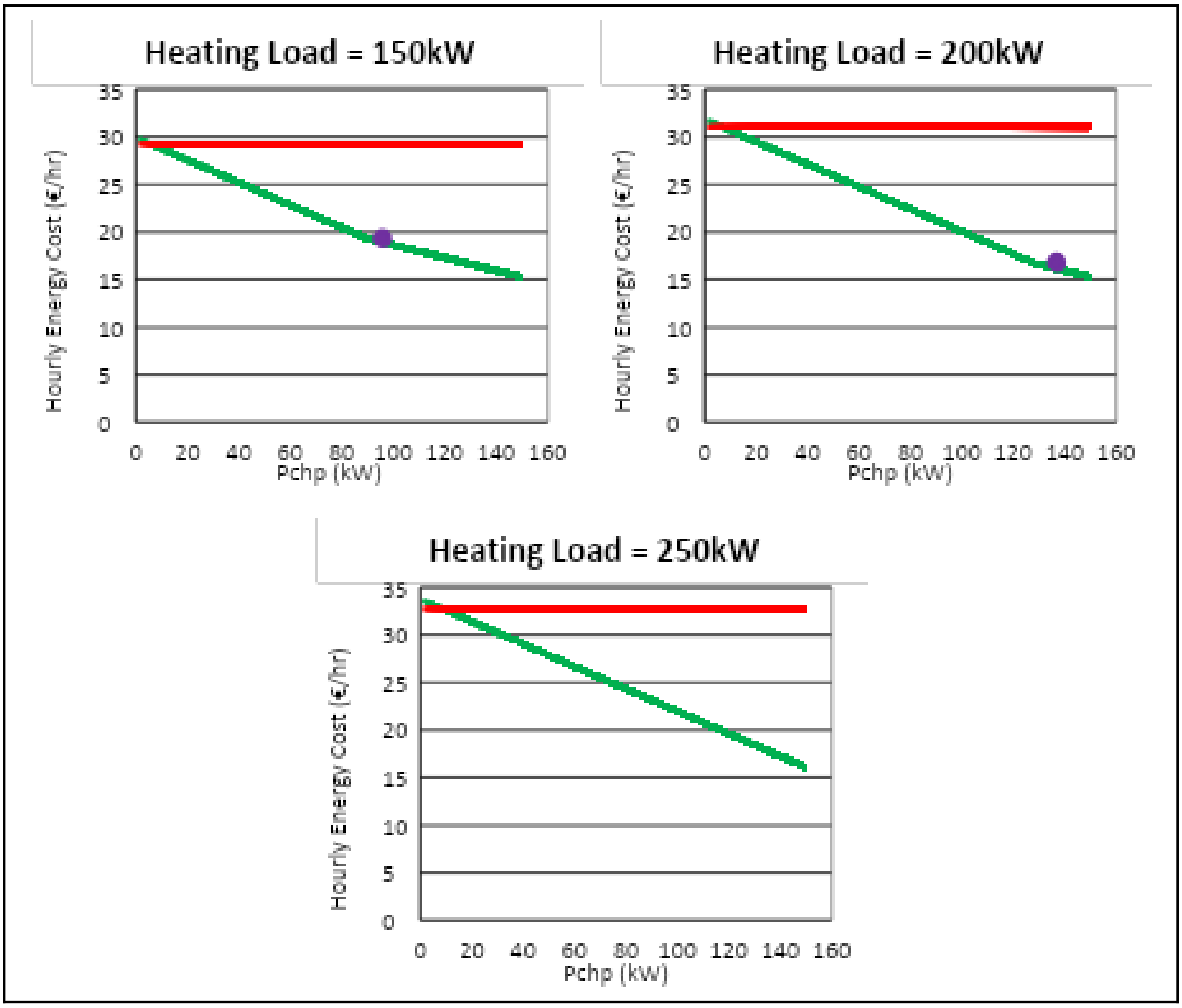
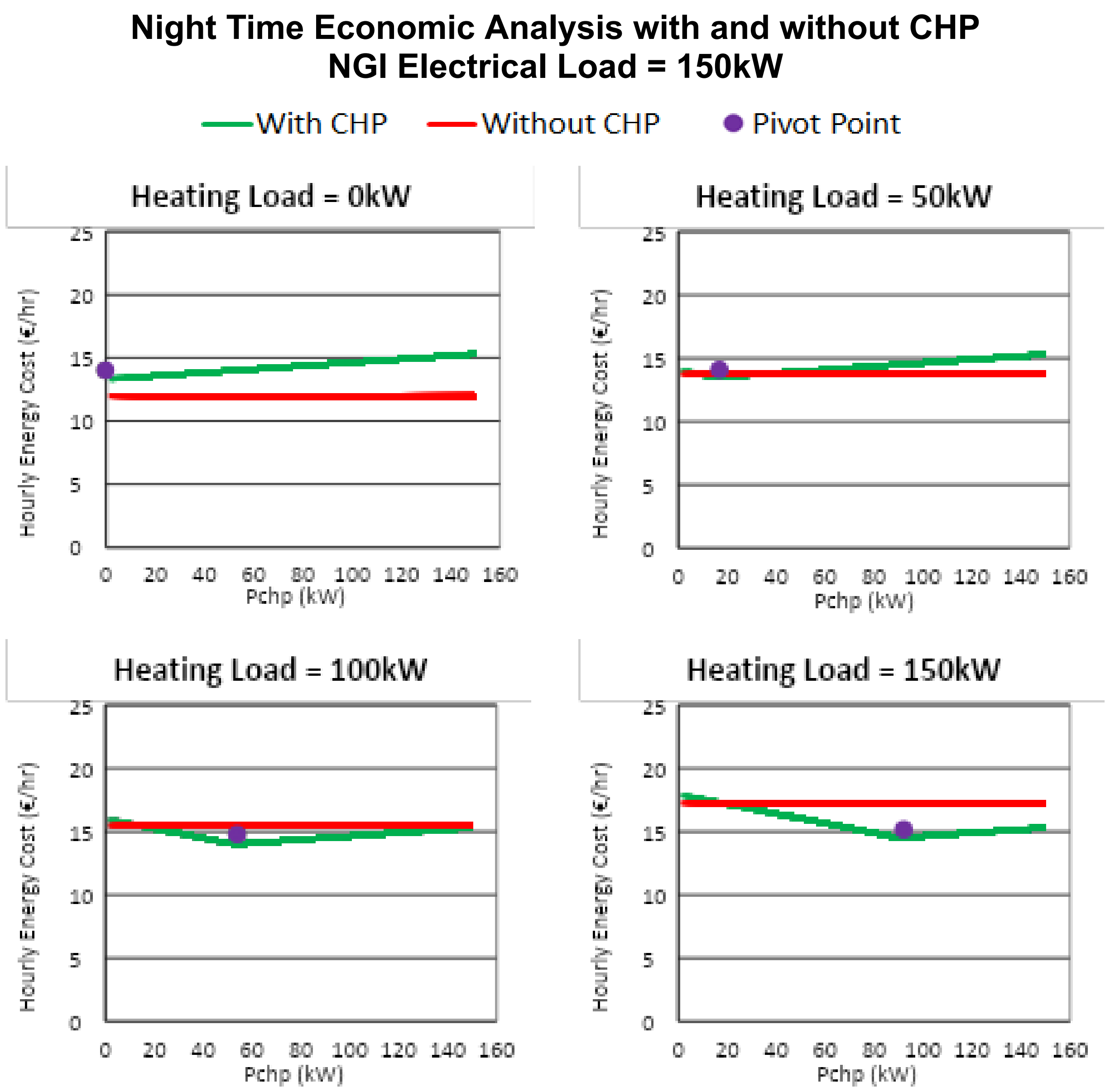


Figure 9-3: Daytime CHP economic analysis


Night Time Economic Analysis with and without CHP
NGI Electrical Load = 150kW
With CHP
Without CHP
Pivot Point
Heating Load = 0kW
Heating Load = 50kW
Heating Load = 100kW
Heating Load = 150kW
Hourly Energy Cost (€/hr)
Pchp (kW)
0
5
10
15
20
25
0
20
40
60
80
100
120
140
160

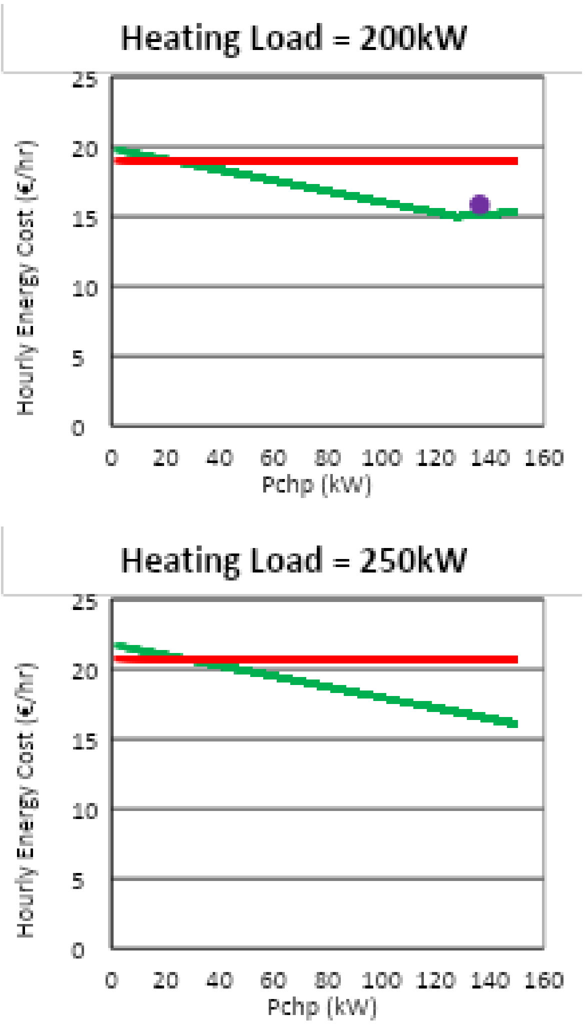


Figure 9-4: Night time CHP economic analysis

9.2.1 Daytime CHP Economic Analysis

Figure 9-3 shows the results from the CHP daytime economic analysis. The first point to note is that the hourly energy cost when not using the CHP is constant for each combination of electrical and heating load. As the heating load increases, the hourly energy cost also increases as the boiler requires more fuel to increase its output. However, the hourly energy cost when the CHP is used doesn't necessarily increase when the heating load increases. This is because previously dumped heat from the CHP may now be used towards the larger heating load.

For example, it costs the same to provide an electrical load of 150kW and a heating load of 50kW using the CHP unit as to provide an electrical load of 150kW and a heating load of 150kW as the previously dumped heat can then be used.

The purple dot along the green line represents the point at which the heat output of the CHP unit matches the heating load exactly. The slope of the green line changes at this point. To the left of the purple dot, all of the heat from the CHP can be used, so there are electrical cost savings and heating cost savings as the power output of the CHP increases. To the right of the purple dot, the heating load has already been satisfied so some of the heat from the CHP must be dumped. To the right of the purple dot, there are only electrical cost savings as the power output of the CHP increases so the slope of the energy cost is more gradual.

The slope of the green line or energy cost line is negative both sides of the purple dot. This means that the power output of the CHP unit should be maximised during the daytime regardless of the heating load available.

9.2.2 Night time CHP Economic Analysis

Figure 9-4 shows the results from the CHP night time economic analysis. Similarly to the daytime analysis, the hourly energy cost when not using the CHP unit increases at larger heating loads whereas the hourly energy cost when using the CHP may not necessarily increase at larger heating loads. It is worth noting that the energy costs when not using the CHP unit are significantly lower for the night time analysis compared to the daytime analysis due to the cheaper electricity tariffs.

As with the daytime analysis, the purple dot along the green line represents the point at which the heat output of the CHP unit matches the heating load exactly. The slope to the left of the purple dot is negative but more gradual than the daytime analysis. This is because the combined heating and electrical savings from using the CHP unit are lower due to the cheaper grid electricity tariff. The slope to the right of the purple dot becomes positive. This is because it is actually cheaper to import electricity from the grid than to increase the power output of the CHP unit.

The energy cost line reaches a minimum when the heat output of the CHP unit equals the heating load. This means that the power output of the CHP unit should be modulated so that 100% of the heat produced by the CHP can be used while maintaining as high a power output as possible. If there is no heating load available the CHP unit should be turned off.

If the power output of the CHP unit is set to the right of the purple dot, the CHP unit may still provide a saving if the energy cost is below the energy cost when not using the CHP unit (i.e. if the green line is still below the red line). However, the cost has not been minimised in this case.

9.2.3 Control Philosophy #1: Minimise Cost

To minimise hourly energy costs, the power output of the CHP unit should be maximised according to the available electrical load during the daytime electrical tariffs regardless of the heating load available.

During night time electrical tariffs, the power output of the CHP unit should be modulated so that its power output is maximised according to the available electrical load and that all of its heat output can be used.

Figure 9-5 was constructed using data from the economic analysis in the previous section. It shows the optimum CHP power output setpoints to minimise cost for given electrical and heating loads. The series are labelled according to the NGI electrical load. For example, the series; *Pload = 50kW*, represents an NGI electrical load of 50kW.

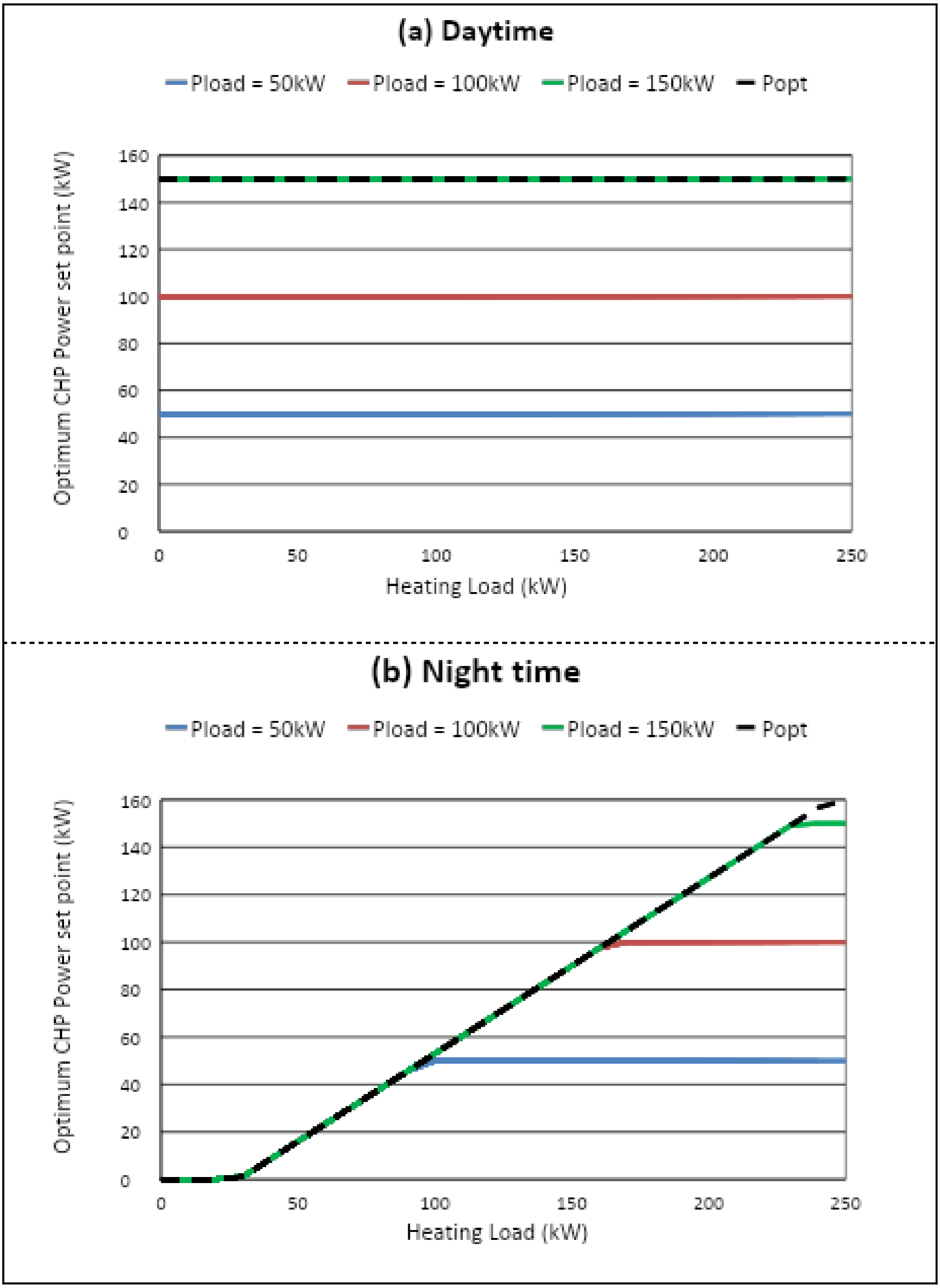


Figure 9-5: Daytime (a) and night time (b) optimum CHP power setpoints to achieve minimum energy costs for a given heating load

9.3 CO_2 Emission Analysis

A CO_2 intensity analysis was carried out to determine when the CHP unit should operate and what power output it should operate at in order to minimise the NGI's CO_2 emissions. The same method was used for the CO_2 emission analysis as was used for the economic analysis.

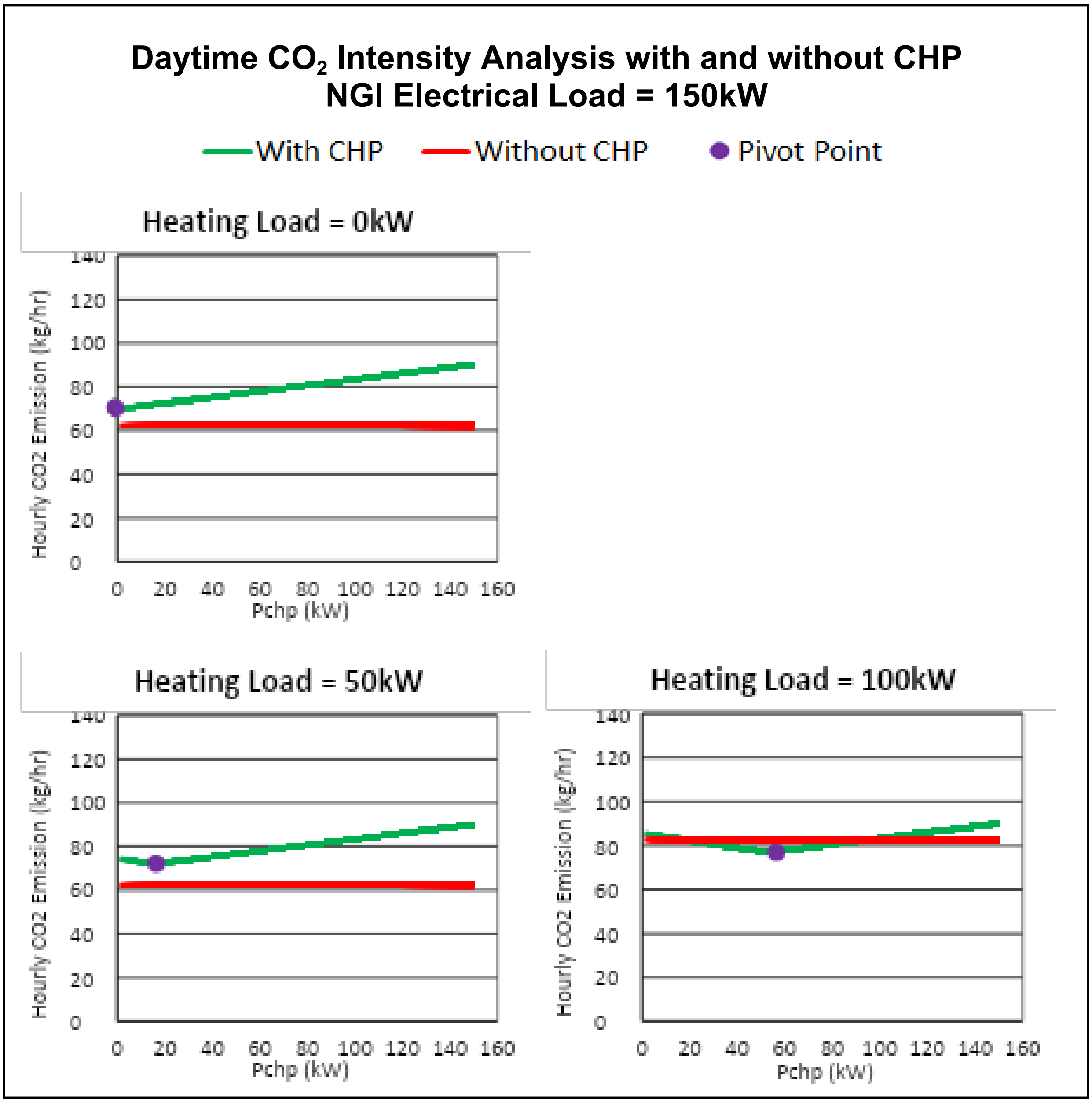
The CO_2 emissions of the NGI building depend on the following factors:

- The NGI heating and electrical loads present
- Whether the CHP unit is operating or not
- The performance of the CHP unit and boilers
- The gas and grid electricity CO_2 intensities

Similarly to the gas tariff in the economic analysis, the CO_2 intensity of gas remains constant throughout the day. The CO_2 intensity of the grid electricity also changes depending on the time of day. However, the CO_2 intensity is higher overnight than during the day which is the opposite of the grid electricity tariffs.

The CO_2 intensity of grid electricity is 0.414kgCO_2/kWh and 0.490kgCO_2/kWh during day and night times respectively. The difference between the day and night CO_2 intensities is not as significant as the difference between day and night grid electricity tariffs. The CO_2 intensity analysis should therefore show similar CO_2 emission trends for both day and night.

Figure 9-6 and Figure 9-7 show the CO_2 emissions calculated for the daytime and night time CO_2 emission analyses respectively. The green lines represent the hourly CO_2 emission when the CHP is used at the given CHP unit power output (labelled *Pchp*). The red line represents the hourly CO_2 emission when the CHP is not used and remains constant for each load combination.



Daytime CO_2 Intensity Analysis with and without CHP
NGI Electrical Load = 150kW
With CHP
Without CHP
Pivot Point
Heating Load = 0kW
Heating Load = 50kW
Heating Load = 100kW
Hourly CO2 Emission (kg/hr)
Pchp (kW)
0
20
40
60
80
100
120
140
160

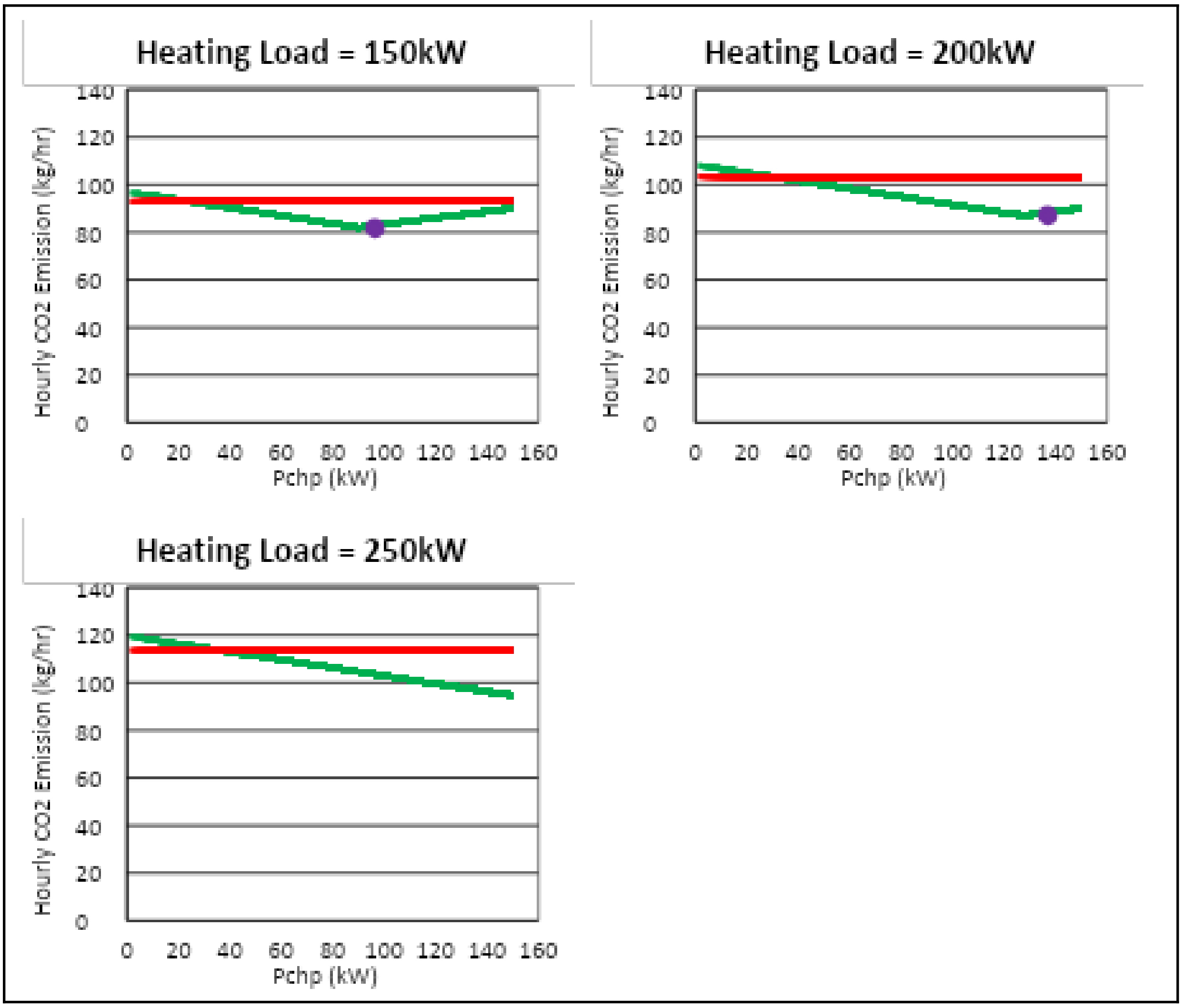
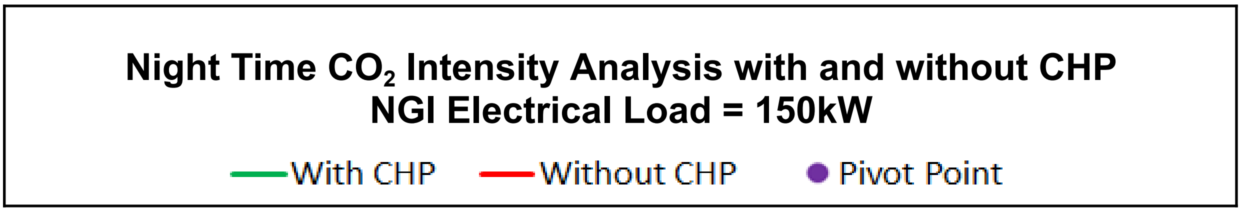
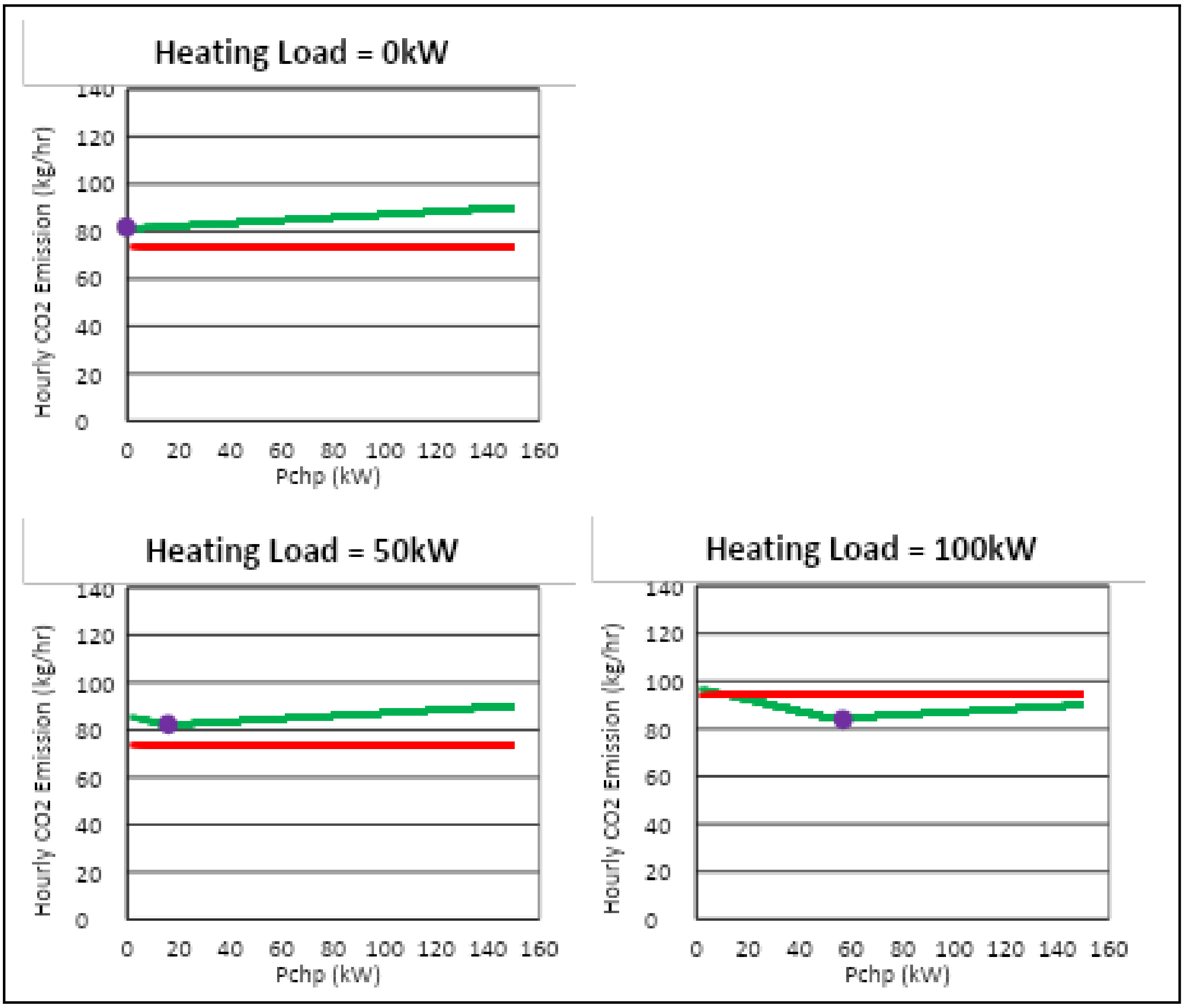


Figure 9-6: Daytime CHP CO_2 intensity analysis





Heating Load = 0kW
Hourly CO2 Emission (kg/hr)
Pchp (kW)
Heating Load = 50kW
Hourly CO2 Emission (kg/hr)
Pchp (kW)
Heating Load = 100kW
Hourly CO2 Emission (kg/hr)
Pchp (kW)

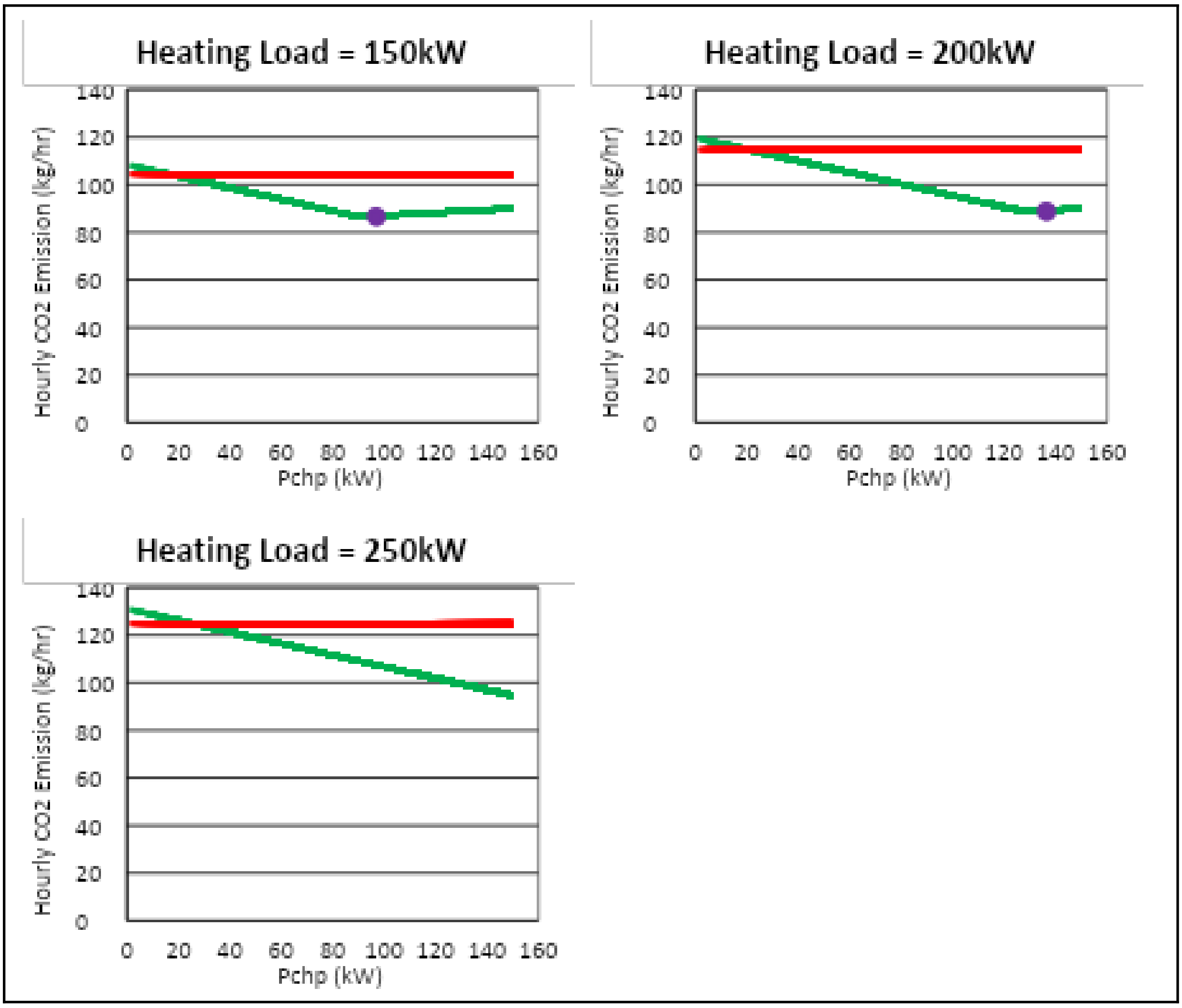


Figure 9-7: Night time CHP CO_2 intensity analysis

9.3.1 Day & Night Time CHP CO_2 Emission Analyses

As expected, the CO_2 emission trends are similar for both the daytime and night time CO_2 emission analyses. The CO_2 emission when using the CHP unit reaches a minimum at the purple dot along the green line or CO_2 emission line. As with the economic analyses, this purple dot represents the point at which the heat output of the CHP unit matches the heating load exactly.

If the CO_2 emissions from the CHP unit have reached a minimum, the CHP unit should still be turned off if the boilers and electrical grid can meet the same loads with less CO_2 emissions (i.e. if the purple dot is above the red line).

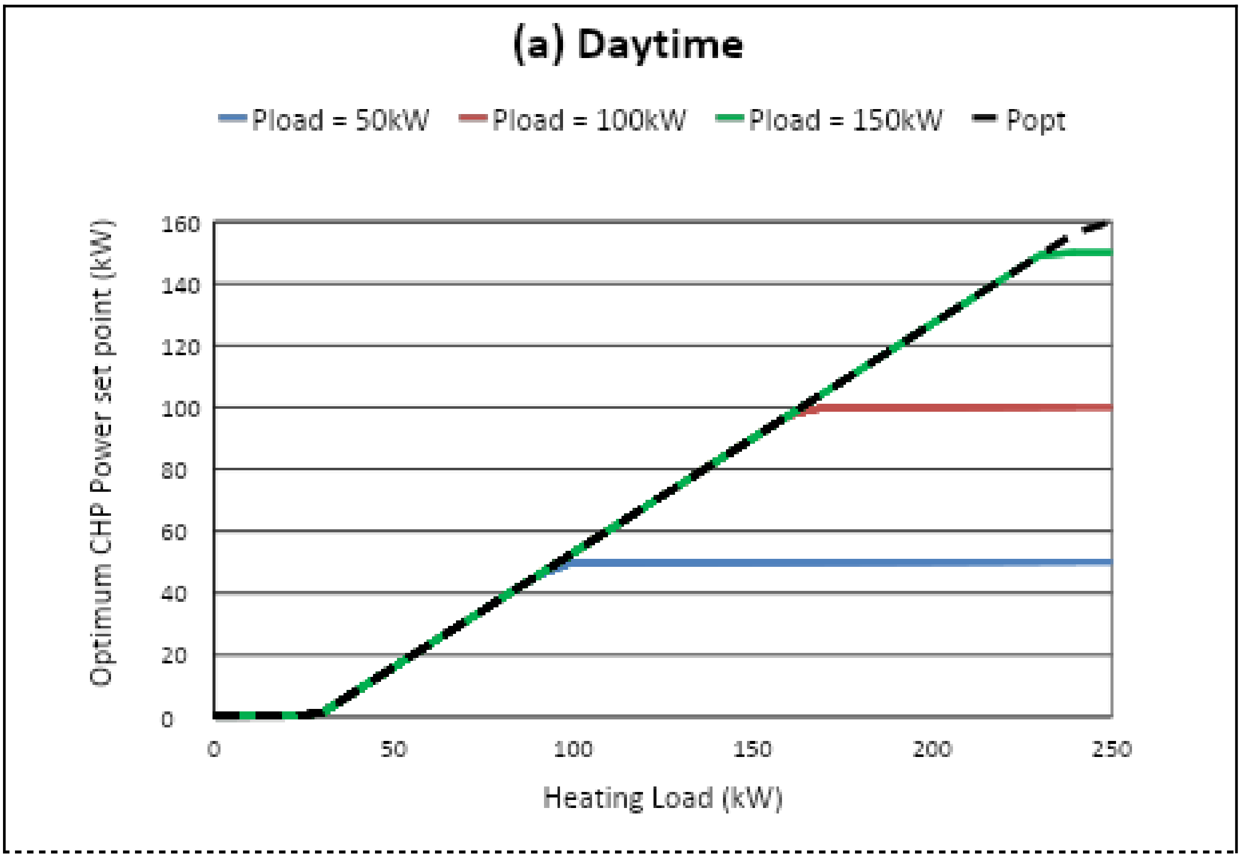
9.3.2 Control Philosophy #2: Minimise CO_2 Emission

The control philosophy used to minimise CO_2 emissions at all times is the same as that used to minimise costs during night time.

To minimise hourly CO_2 emissions, the power output of the CHP unit should be modulated so that its power output is maximised according to the available electrical load and that all of its heat output can be used.

Figure 9-8 was constructed using data from the CO_2 emission analysis in the previous section. It shows the optimum CHP power output setpoints to minimise CO_2 emissions for given electrical and heating loads. The series are labelled according to the NGI electrical load. For example, the series; *Pload = 50kW*, represents an NGI electrical load of 50kW.

There is a very slight difference between the optimum CHP power output setpoints during daytime and night time due to the relative small difference between daytime and night time grid electricity CO_2 intensities.



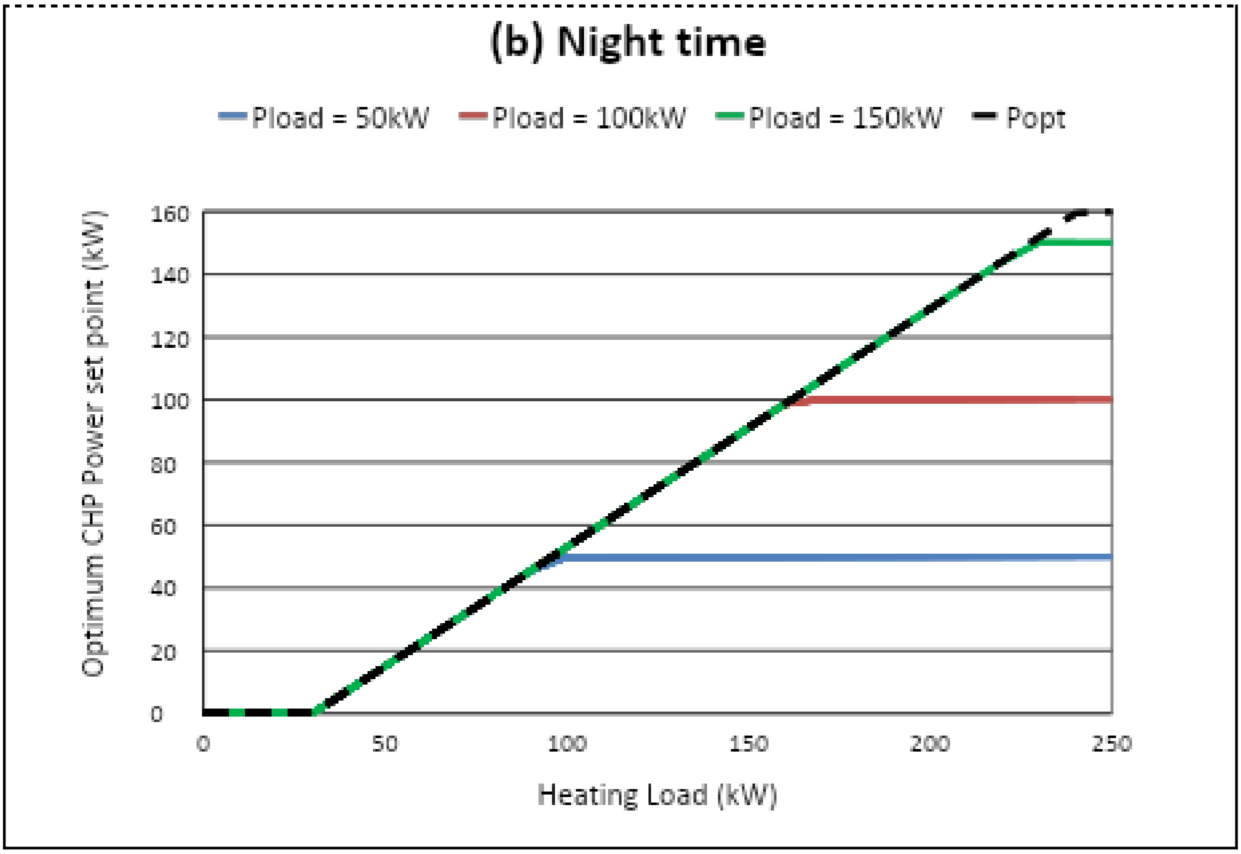


Figure 9-8: Daytime (a) and night time (b) optimum CHP power setpoints to achieve minimum CO_2 emissions for a given heating load

9.4 CHP Heat Priority

The minimum cost and minimum CO_2 emission control philosophies developed depend on the available NGI heating load. The NGI heating load may be provided by the CHP unit, the heat recovery chiller, the boilers or a combination of each.

The CHP unit and boilers may provide both the higher temperature heating load and the lower temperature heating load. The heat recovery chiller may only provide the lower temperature heating load. If the CHP unit satisfies any of the lower temperature heating load, it is effectively stealing the load from the heat recovery chiller. Therefore the CHP unit meets any higher temperature heating loads before meeting any of the lower temperature heating loads.

During summer, there is a larger potential for heat recovery from the chiller due to the higher cooling loads. However, both the high temperature and low temperature heating loads are relatively small during the summer. This means that the CHP unit usually steals the lower temperature heating load from the chiller. It may be more economical or less CO_2 intensive to prevent the CHP unit stealing the chiller's heating load and allow the chiller to use any recoverable heat.

Simulations were carried out to determine if the CHP unit should be given heat priority ahead of the chiller for each control philosophy used.

9.4.1 Simulation Results

Figure 9-9 shows the chiller's performance for the simulations that have CHP heat priority and simulations which gave chiller heat priority. The chiller was able to operate in total recovery and cooling main modes for a higher percentage of the year when chiller heat priority was used. The COP ranges of the chiller over the year improved with an average COP of 3.96 when chiller heat priority is used compared to an average COP of 3.87 when CHP heat priority is used.

Although the chiller's performance improved when using chiller heat priority, the heating loads available to the CHP were reduced. This resulted in more heat from the CHP unit being dumped when minimising cost and the CHP unit power output being reduced when minimising CO_2 emissions.

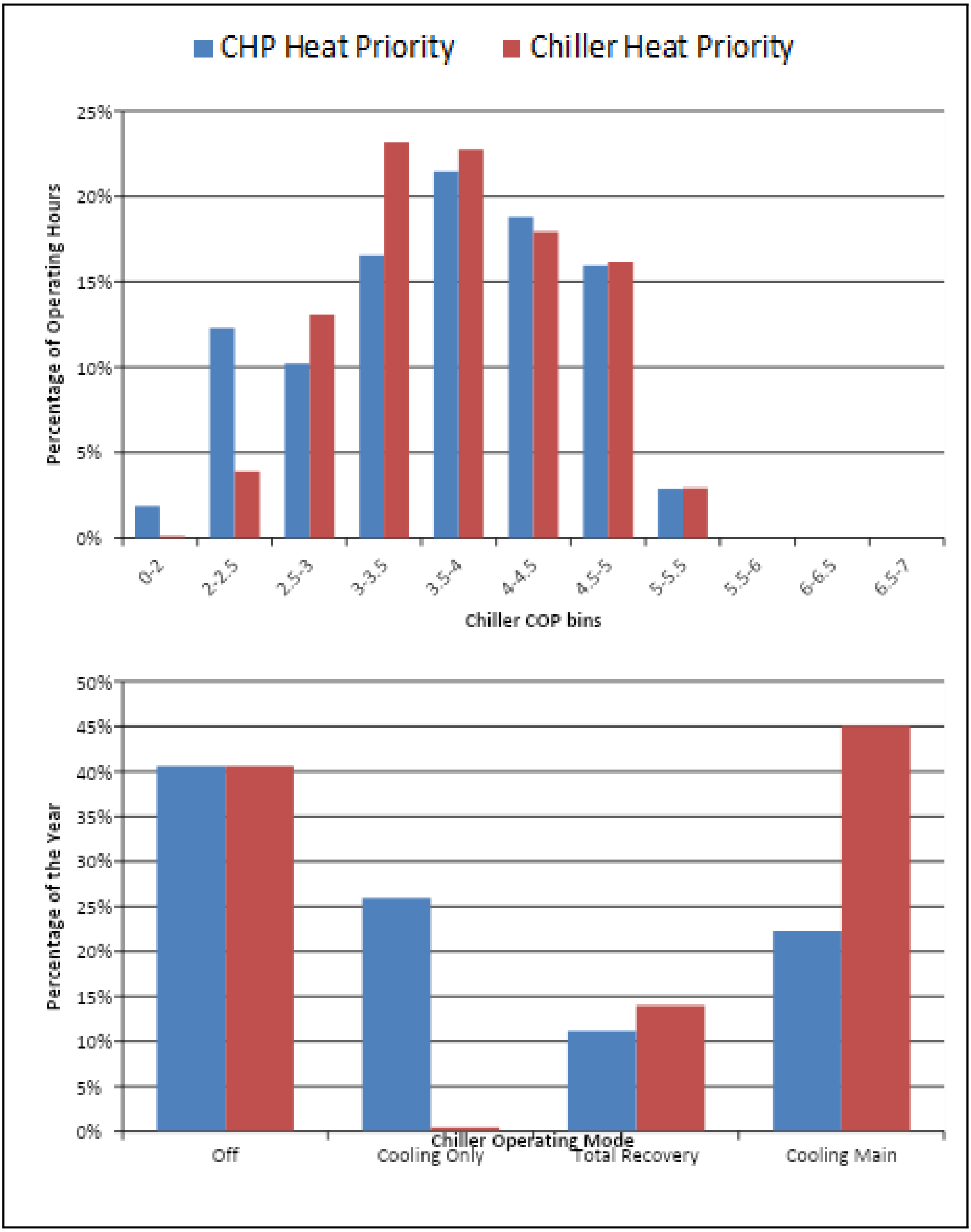


Figure 9-9: Chiller performance for CHP heat priority and chiller heat priority

Figure 9-10 shows the annual energy costs when minimising cost for both CHP heat priority and chiller heat priority. It also shows the annual CO_2 emissions when minimising CO_2 emissions for both CHP heat priority and chiller heat priority. It can be seen that both the annual energy cost and CO_2 emission are lower when CHP heat is given priority ahead of chiller heat. This means that the savings achieved from utilising more of the CHP heat outweigh the savings achieved from a higher chiller performance. CHP heat should therefore be given priority over chiller heat at all times.

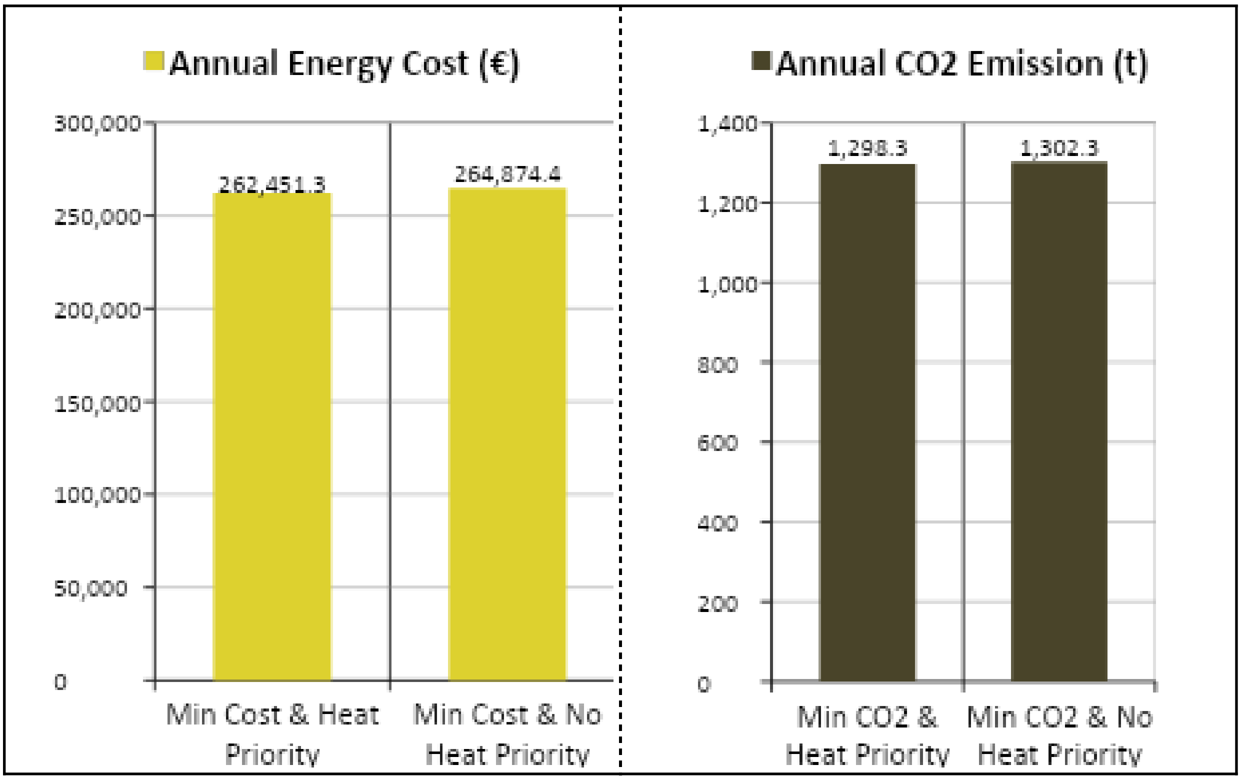


Figure 9-10: Annual energy cost and annual CO_2 emissions for CHP heat priority or chiller heat priority with corresponding control philosophies

9.5 CHP Control Philosophies

The optimum CHP control philosophies for minimising energy costs or CO_2 emissions were determined in this chapter.

The optimum CHP control philosophy for minimising energy costs should:

- Use CHP heat ahead of chiller heat
- During daytime electrical tariffs:

    - Maximise the CHP unit's power output according to the available NGI electrical load
- During night time electrical tariffs:
    - Maximise the CHP unit's power output according to the available NGI electrical load while ensuring that 100% of the heat generated can be used

The optimum CHP control philosophy for minimising CO_2 emissions should:

- Use CHP heat ahead of chiller heat
- Maximise the CHP unit's power output according to the available NGI electrical load while ensuring that 100% of the heat generated can be used

10 Optimum Ice Bank Control Philosophy

This chapter addresses the second thesis objective of determining the optimum ice bank control philosophy. Figure 10-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

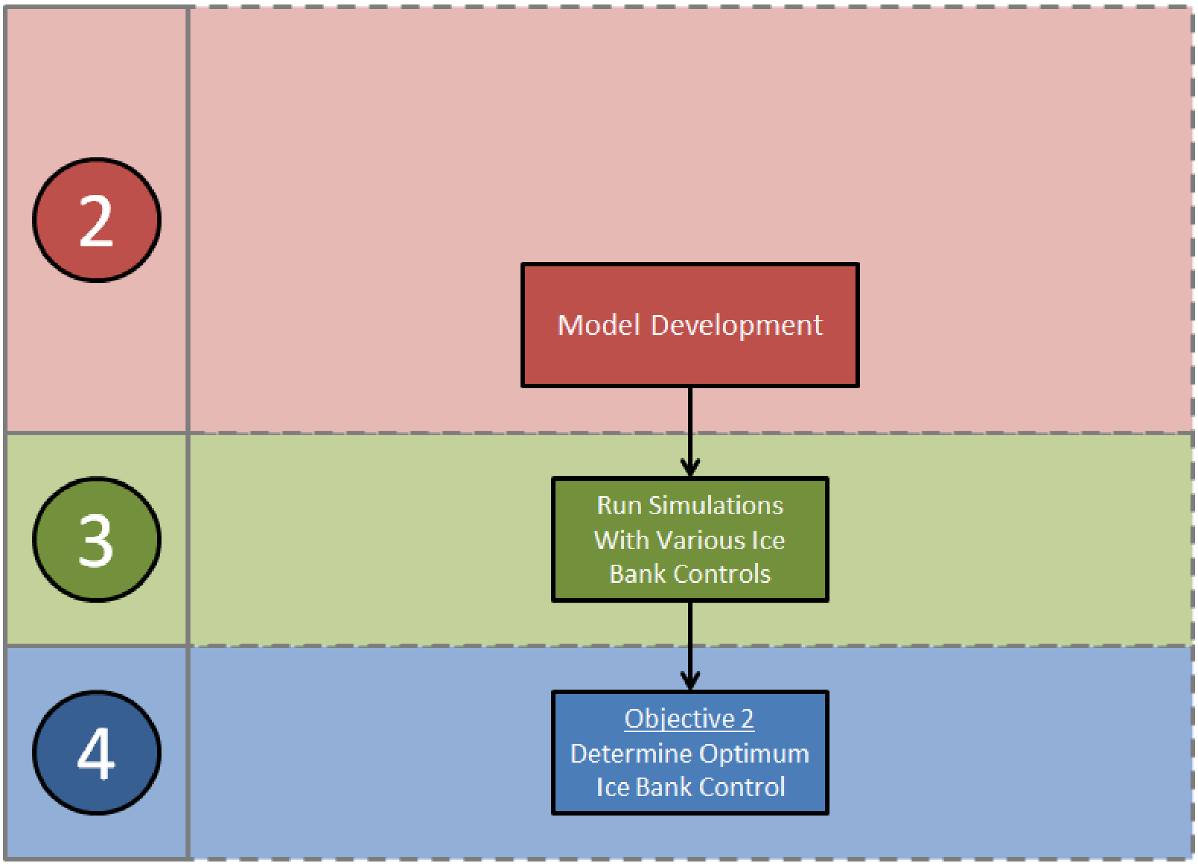


Figure 10-1: Chapter 10 process diagram tasks

10.1 Introduction

The ice bank is used to shift the NGI's cooling load from on peak electrical tariff periods to off peak electrical tariff periods, i.e. from daytime to night time. The ice bank is charged by the chiller during the charging period and is then used to provide some or the entire cooling load during the discharge period.

The ice bank should be charged and discharged in such a way as to optimise the performance of the chiller over the course of a day. The chiller's performance depends on the heating and cooling loads available, the ambient air temperature, its

PLR and its operating mode. The ice bank has the ability to influence each of these factors.

The ice bank can change the cooling load available to the chiller by changing its charge or discharge rate. This increases or decreases the PLR of the chiller and alters the frequency of each operating mode. The ice bank can also change the ambient air temperature experienced by the chiller by charging and discharging during colder or hotter ambient air temperatures.

The chiller performance alone is not enough to determine the optimum ice bank control philosophy. A higher average COP may not necessarily correspond to the lowest annual energy costs or CO_2 emissions as the higher COPs may occur during either day or night times when the grid electricity cost and CO_2 intensities are different. Any effects on the CHP and boiler performance must also be considered. For this reason the total annual energy cost and CO_2 emission were used as deciding factors for the optimum ice bank control philosophy.

There are a number of charging and discharging options that the optimum ice bank control philosophy may use. These options are described in the following sections. Each option was then analysed to determine the optimum charge and discharge combination for the ice bank control philosophy.

10.2 Charging the Ice Bank

The ice bank must be charged by the chiller during each charging period to ensure that it is fully charged before the beginning of the following discharge period. The charging period for the following analyses was set from 23:00 to 08:00, corresponding to the off peak grid electrical tariffs. The ice bank may or may not be charging during the entire charging period, depending on the charging option selected.

Three charging options were analysed; *prolonged charge*, *chiller load dependent charge* and *ambient air temperature dependent charge*. The following sections explain each charging control option. Sample charging loads for prolonged charge, chiller load dependent charge and ambient air temperature dependent charge options during both summer and winter are shown in Figure 10-2, Figure 10-3 and Figure 10-4 respectively in the following sub sections.

Area charts are used in these figures to represent the kWh values of the cooling and charging loads. The NGI cooling load is shown as the dark blue shaded area and the charging loads are shown as the light blue shaded area. The same amount of charging is required to fully charge the ice bank regardless of the charging option used. Therefore the area of the light blue shaded area remains the same for all charging options but its shape differs. The NGI cooling load and charging load are cumulative so the total cooling load experienced by the chiller in kWh is represented by the entire shaded area.

10.2.1 Prolonged Charge

The *prolonged charge* option extends the charge of the ice bank over the entire charging period. This provides a constant and relatively low charging load. It would be difficult in practice to ensure that the charging of the ice bank finished exactly at the end of the charging period. The charging period was shortened by one and a half hours for this charging option to account for this practical issue.

Figure 10-2 shows the charging loads resulting from the prolonged charge option. It can be seen that the charging load remains constant over the shortened charging period. The charging load remains constant at approximately 140kW and 85kW in summer and winter respectively. The resultant chiller load while the ice bank is charging is approximately 180kW in summer, rising to 200kW as the NGI cooling load increases and approximately 120kW during winter.

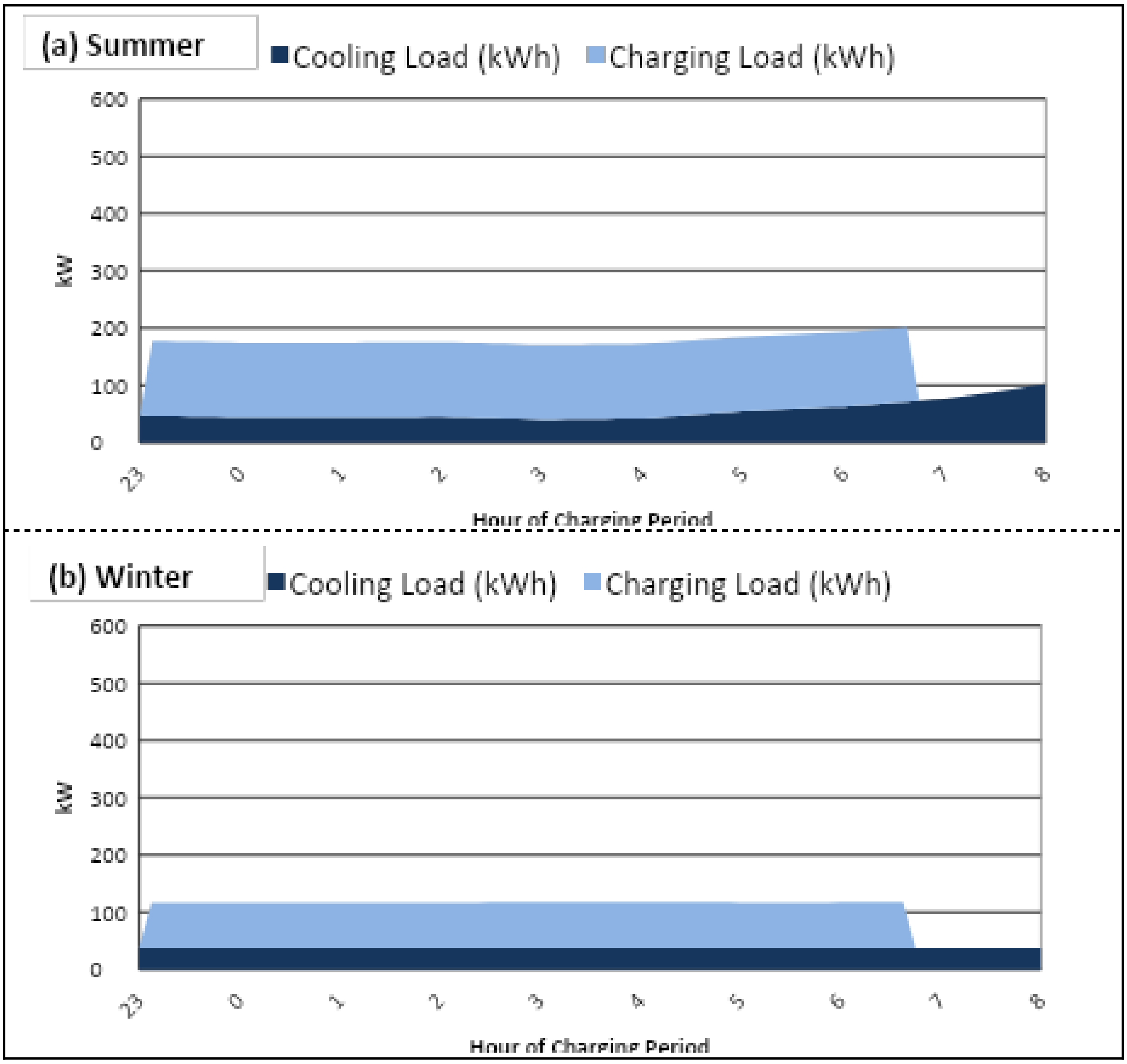


Figure 10-2: Prolonged charge control for (a) summer and (b) winter

10.2.2 Chiller Load Dependent Charge

The chiller load dependent charge option adjusts the charging load so that the resulting chiller load will cause the chiller to operate at its optimal PLR. The chiller's optimal PLR corresponds to a cooling load of approximately 550kW. If for example, the NGI cooling load during the charging period was 250kW, the chiller load dependent charge option would set the charge rate at 300kW. The chiller would therefore have to provide the NGI cooling load of 250kW and the charging load of 300kW, resulting in a combined cooling load of 550kW, corresponding to its optimal PLR.

The charge rate that could be set by the chiller load dependent control was limited to 450kW. If the required charge rate to reach a combined cooling load of 550kW was greater than 450kW, the charge rate upper limit of 450kW was used.

Figure 10-3 shows the charging loads resulting from the chiller load dependent charge option. It can be seen that the charging load is much greater than that for the prolonged charge option. However, the same amount of cooling energy is required to charge the ice bank. Therefore this larger charging load is present for a shorter duration compared to the prolonged charge control option.

The resulting chiller load while the ice bank is charging is just under 500kW. A chiller load of 550kW could not be reached as the NGI cooling load was relatively low and the upper charge rate limit of 450kW had to be applied. The charge rate remains constant while charging simply due to the constant NGI building load. If the NGI building load was not constant and the optimal resultant chiller load had been reached, the charge rate would be adjusted accordingly.

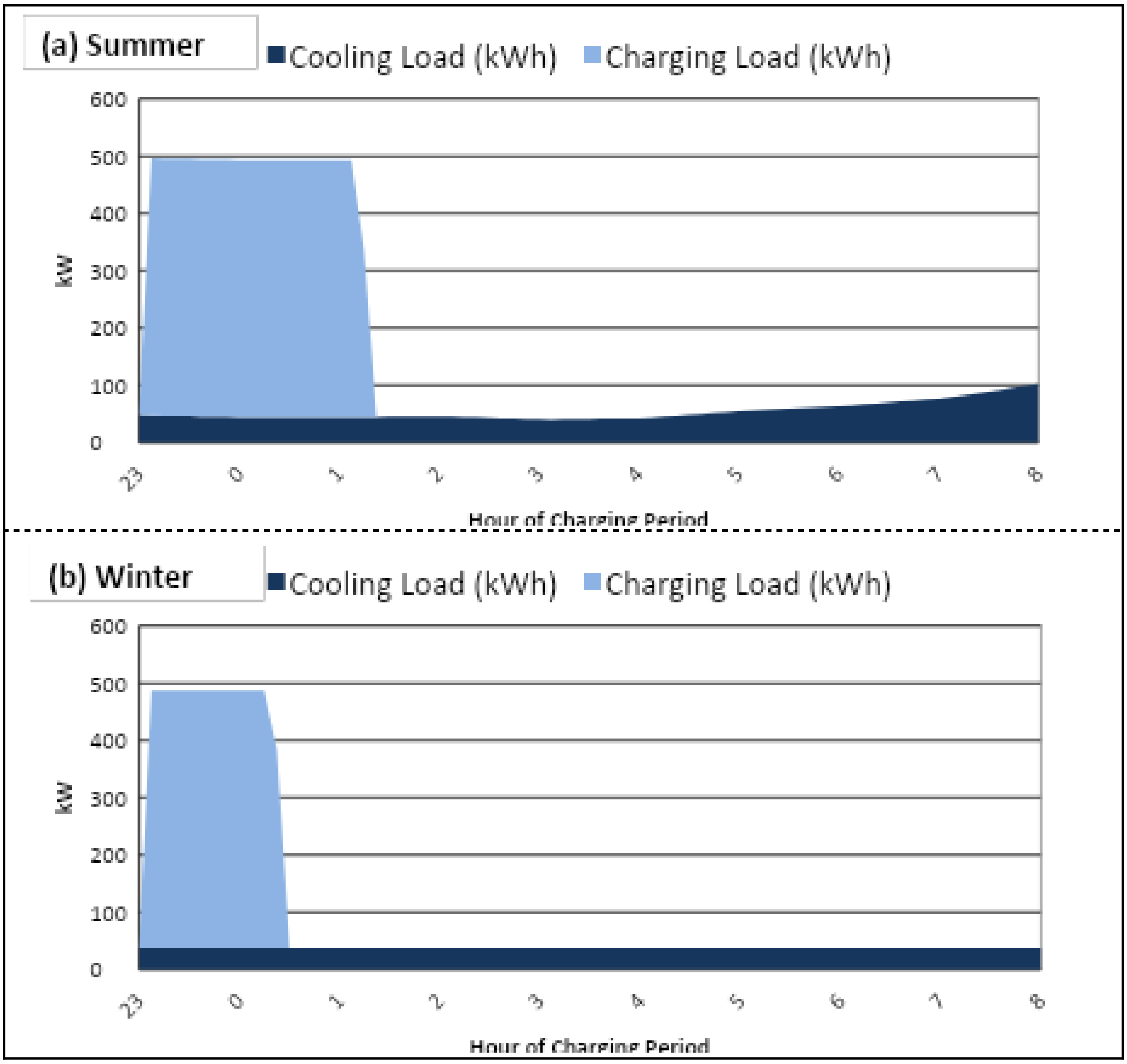


Figure 10-3: Chiller load dependent charge control for (a) summer and (b) winter

10.2.3 Ambient Air Temperature Dependent Charge

The ambient air temperature dependent charge option adjusts the charge rate so that the optimal chiller load is reached similarly to the chiller load dependent charge option. With the chiller load dependent charge option, charging begins at the beginning of the charging period. However, with the ambient air temperature dependent charge option, charging doesn't begin until the ambient air temperature approaches the minimum predicted air temperature for that charging period. This is done to improve the chiller's performance.

The ambient air temperature over the charging period must be predicted for this charging option to be practical. If the minimum ambient air temperature over the charging period occurs towards the end of the charging period, charging will begin while a predefined number of charging hours remain.

Figure 10-4 shows the charging loads resulting from the ambient air temperature dependent charge option. Figure 10-4 also includes the ambient air temperature profile over the charging period. It can be seen that the charging loads are the same as those for the chiller load dependent option. However, the summer charging load occurs at a different time during the charging period. This is because charging doesn't begin until the ambient air temperature approaches the minimum ambient air temperature during the charging period. The charging load occurs at the same time in winter because the minimum ambient temperature happens to occur at the start of the charging period.

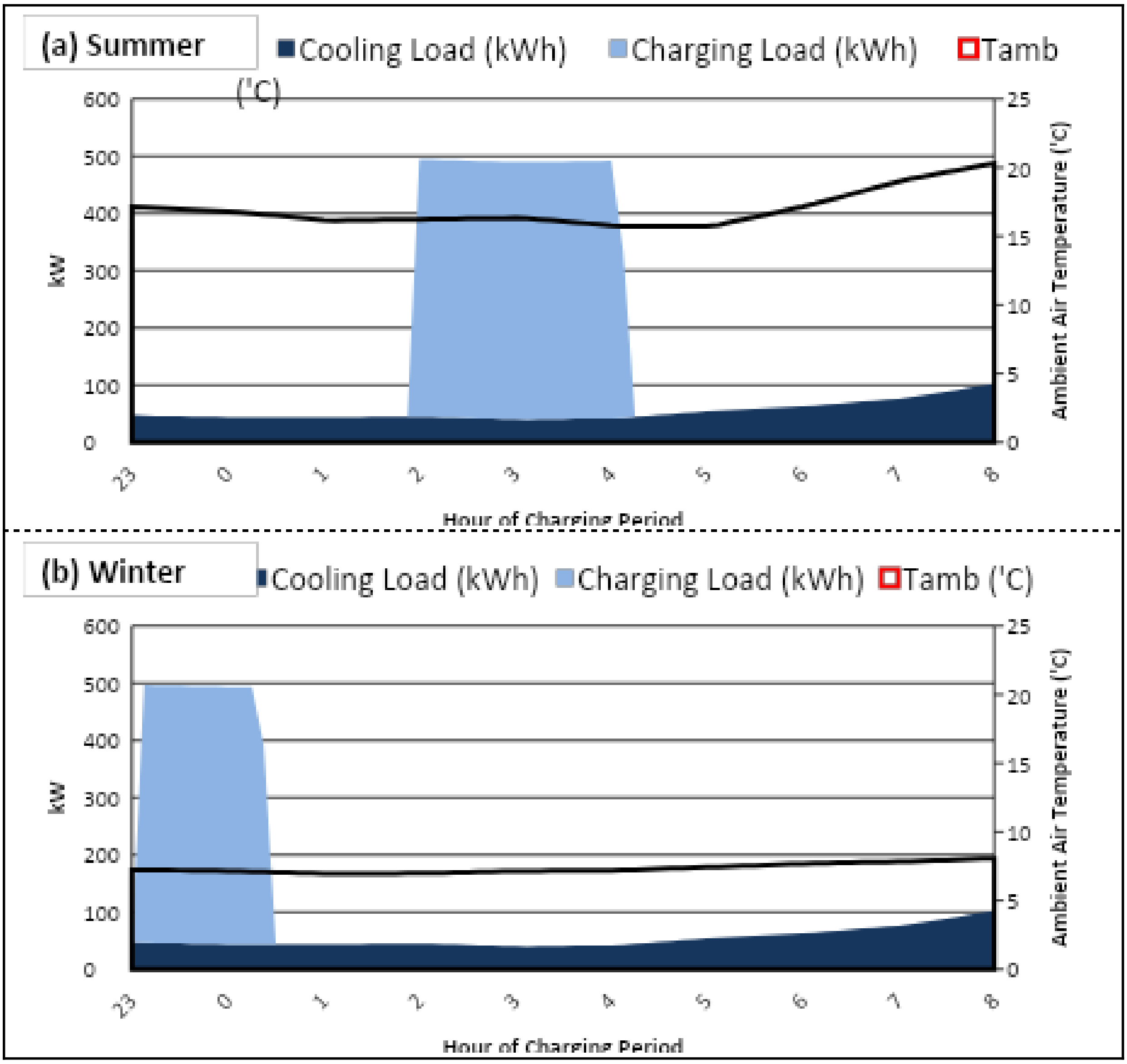


Figure 10-4: Ambient air temperature dependent charge control for (a) summer and (b) winter

10.3 Discharging the Ice Bank

The ice bank is discharged during on peak grid electricity tariffs to reduce the electrical demand on the grid caused by the chiller. The discharging period was set from 08:00 to 23:00, corresponding to these higher gird electricity tariffs. The ice bank may or may not be discharging during the entire discharging period, depending on the discharging option selected.

Four discharging options were analysed; *store priority*, *chiller priority*, *constant proportion* and *level chiller*. The following sections explain each discharging control option. Sample discharging loads for store priority, chiller priority, constant proportion of 25%, constant proportion of 100% and level chiller discharge options during both summer and winter are shown in Figure 10-5, Figure 10-6, Figure 10-7, Figure 10-8 and Figure 10-9 respectively.

Area charts are used in a similar fashion to the charging control option section. The cooling load provided by the chiller is shown as the dark blue shaded area and the cooling load provided by the ice bank is shown as the light blue shaded area. These loads are cumulative so the total cooling load provided is represented by the entire shaded area. Unlike the graphs for the charging controls, the area of the light blue shaded area does not remain constant. This is because the cooling provided by the ice bank differs slightly depending on the discharge control used.

10.3.1 Store Priority Control

With store priority control, the ice bank is given priority use ahead of the chiller. The ice bank provides cooling for the entire discharge period so that it is fully depleted by the end of the discharging period. Any cooling that cannot be provided by the ice bank is provided by the chiller.

Figure 10-5 shows the cooling loads provided by the ice bank when store priority discharge control is used. It can be seen that the ice bank provides a base load of cooling in the summer with the remainder of the cooling provided by the chiller. During winter, the ice bank is capable of providing the entire cooling load.

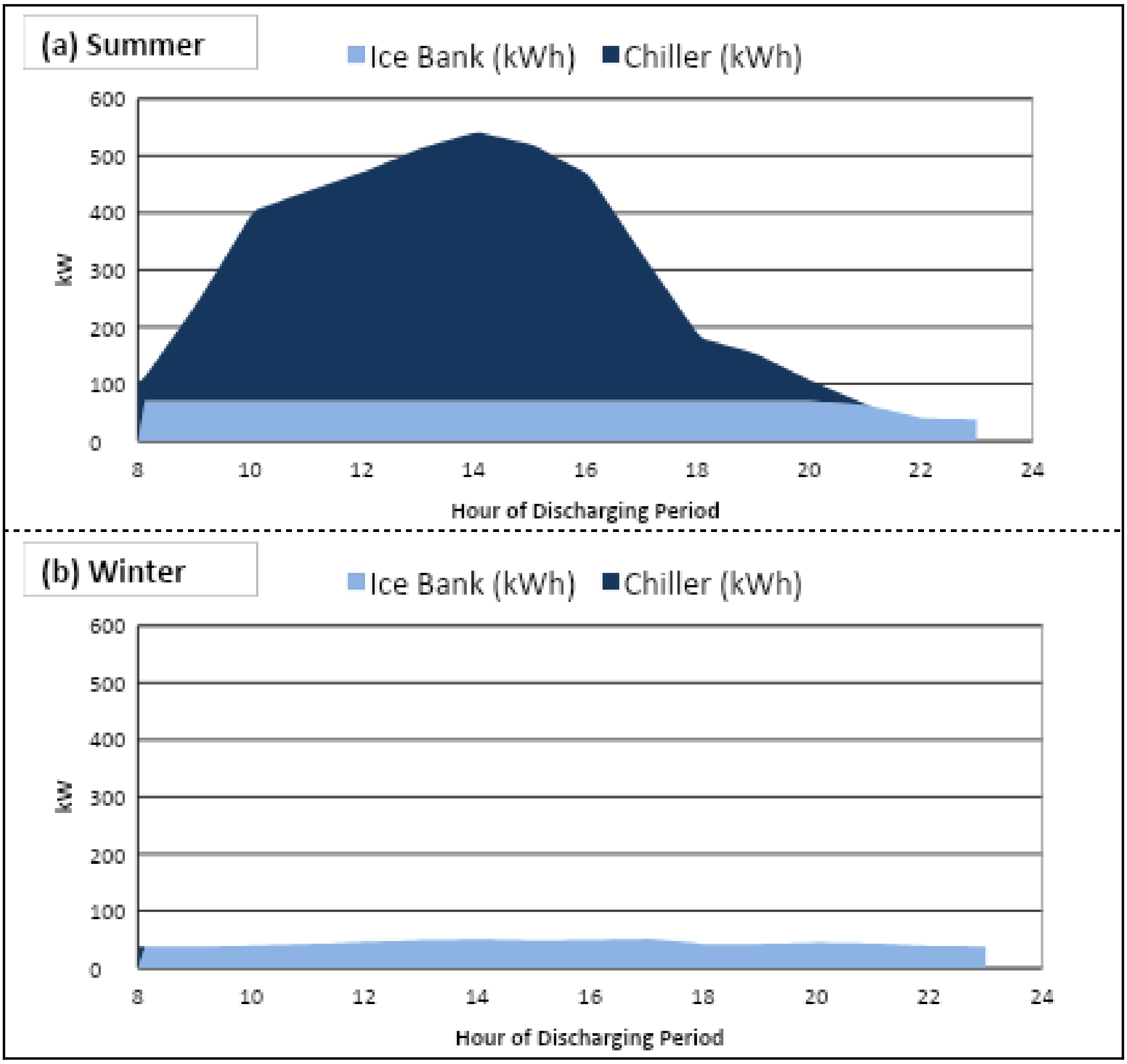


Figure 10-5: Store priority discharge control for (a) summer and (b) winter

10.3.2 Chiller Priority Control

With chiller priority control, the chiller runs at full capacity. The ice bank provides any cooling that cannot be provided by the chiller. If the ice bank has sufficient charge to provide the remaining cooling loads for the discharge period, the chiller turns off and the ice bank provides all of the cooling. One of the benefits of chiller priority is to allow the chiller to be downsized.

The chiller used in the model was not downsized. It used the same performance equations as the existing chiller model but an additional maximum cooling limit was used to mimic the downsizing of the chiller. The additional maximum cooling limit applied was 450kW. This figure corresponded to the approximate minimum that would ensure that the cooling load could be met all year round with the existing ice bank capacity.

Figure 10-6 shows the cooling loads provided by the ice bank when chiller priority discharge control is used. It can be seen that the chiller operates at full capacity until the remainder of the cooling load can be provided by the ice bank. The ice bank provides any additional cooling required when the chiller is operating at full capacity. The ice bank has enough capacity to provide the entire cooling load during the winter.

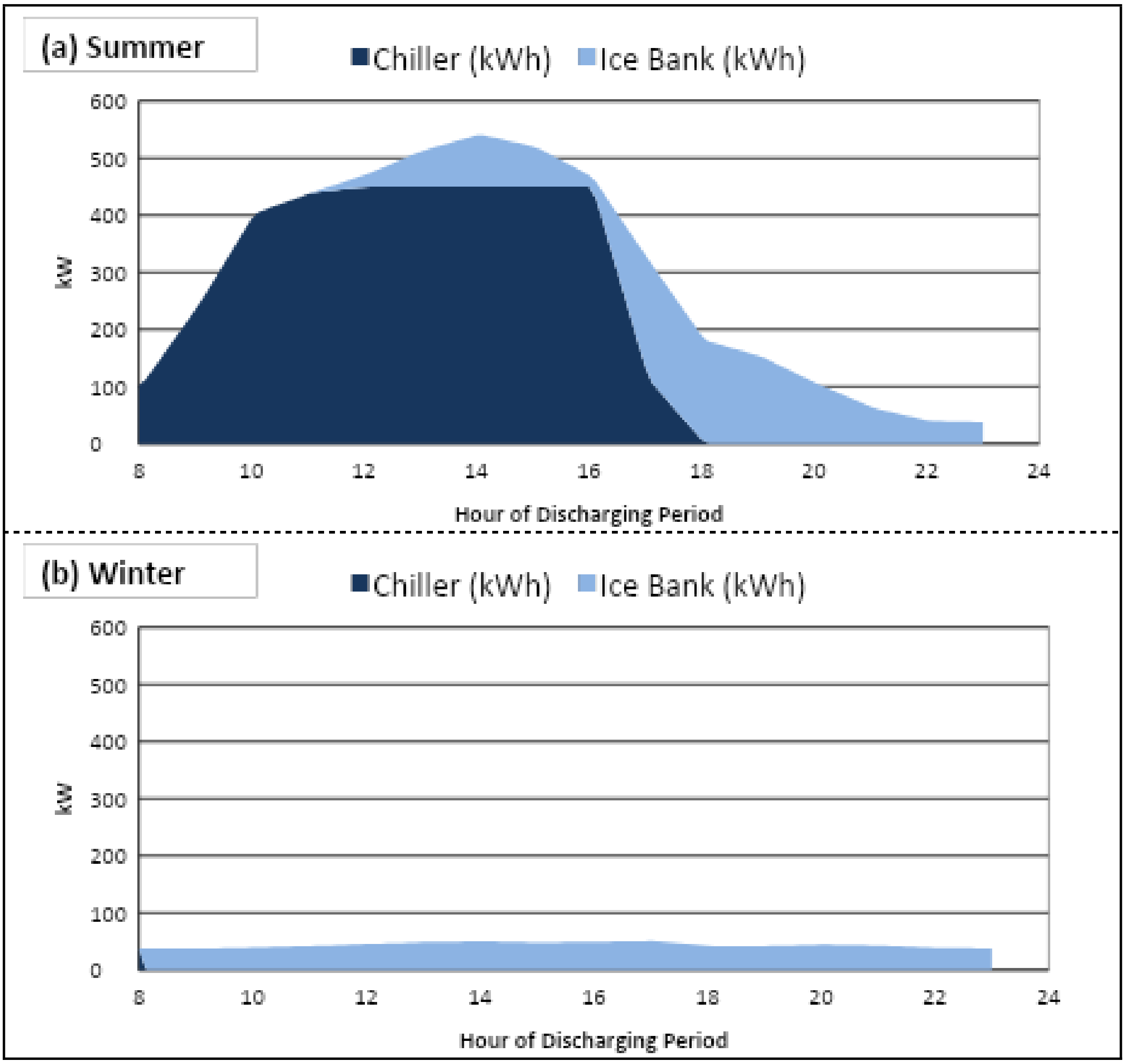


Figure 10-6: Chiller priority discharge control for (a) summer and (b) winter

10.3.3 Constant Proportion

Constant proportion discharge control is the most simple discharge option. A constant proportion of the cooling load is provided by the ice bank and the remainder is provided by the chiller. The constant proportion used will determine if the ice bank depletes fully, doesn't deplete fully or depletes prematurely.

Figure 10-7 and Figure 10-8 show the cooling loads provided by ice bank using constant proportion discharge control with a constant proportion of 25% and 100% respectively.

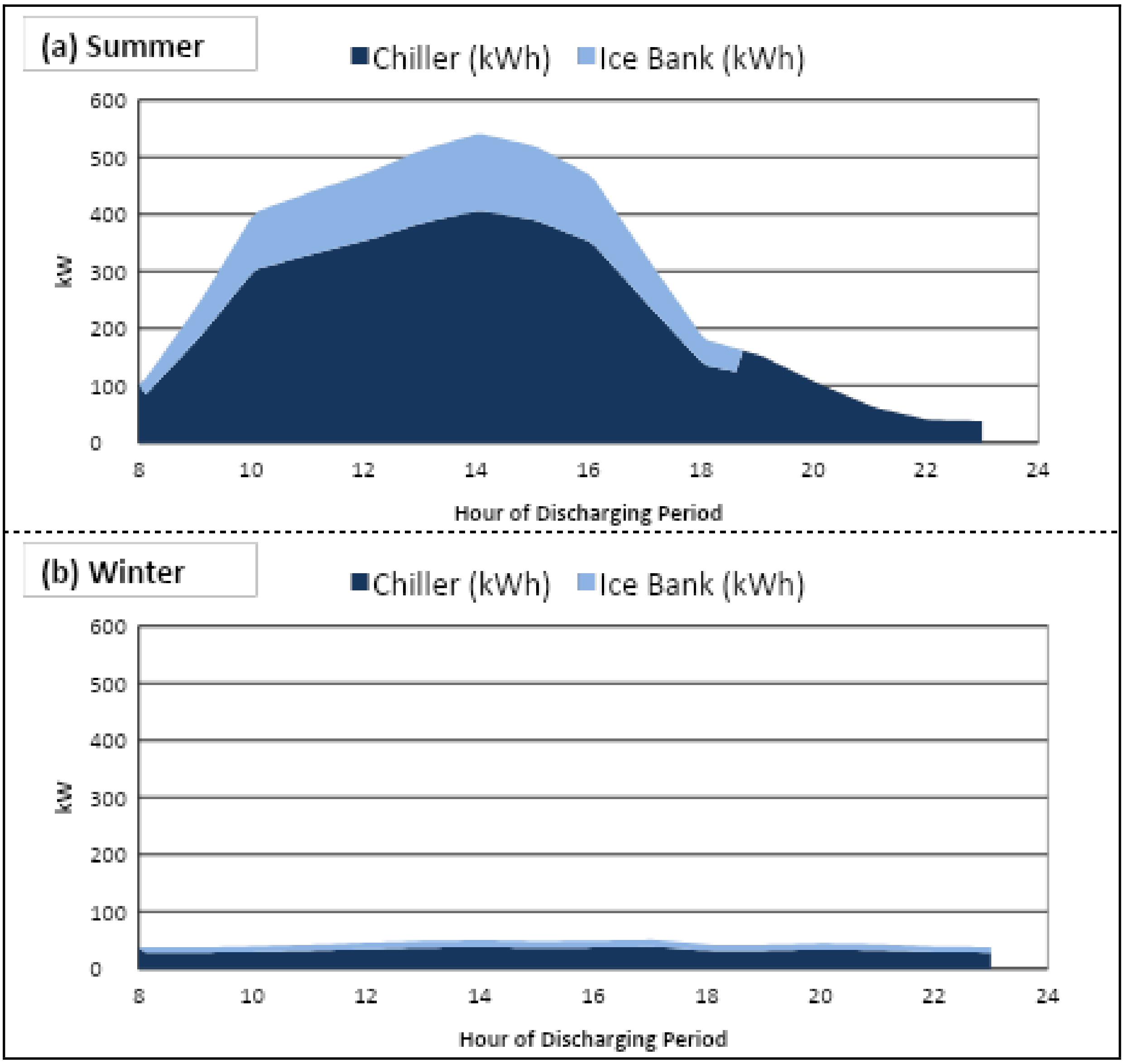


Figure 10-7: Constant proportion discharge control of 25% for (a) summer and (b) winter

It can be seen from Figure 10-7 that when a constant proportion of 25% is used in summer, the ice bank reduces the peak load to be met by the chiller and depletes in the evening time. However, during winter, a constant proportion of 25% results in only a fraction of the ice bank's cooling potential being used and the chiller operating when it is unnecessary to do so.

It can be seen from Figure 10-8 that when a constant proportion of 100% is used in summer, the ice bank quickly depletes and the chiller must meet the peak cooling demand on its own. However, when a constant proportion of 100% is used during winter, the ice bank can fully meet the cooling load and the chiller can remain off.

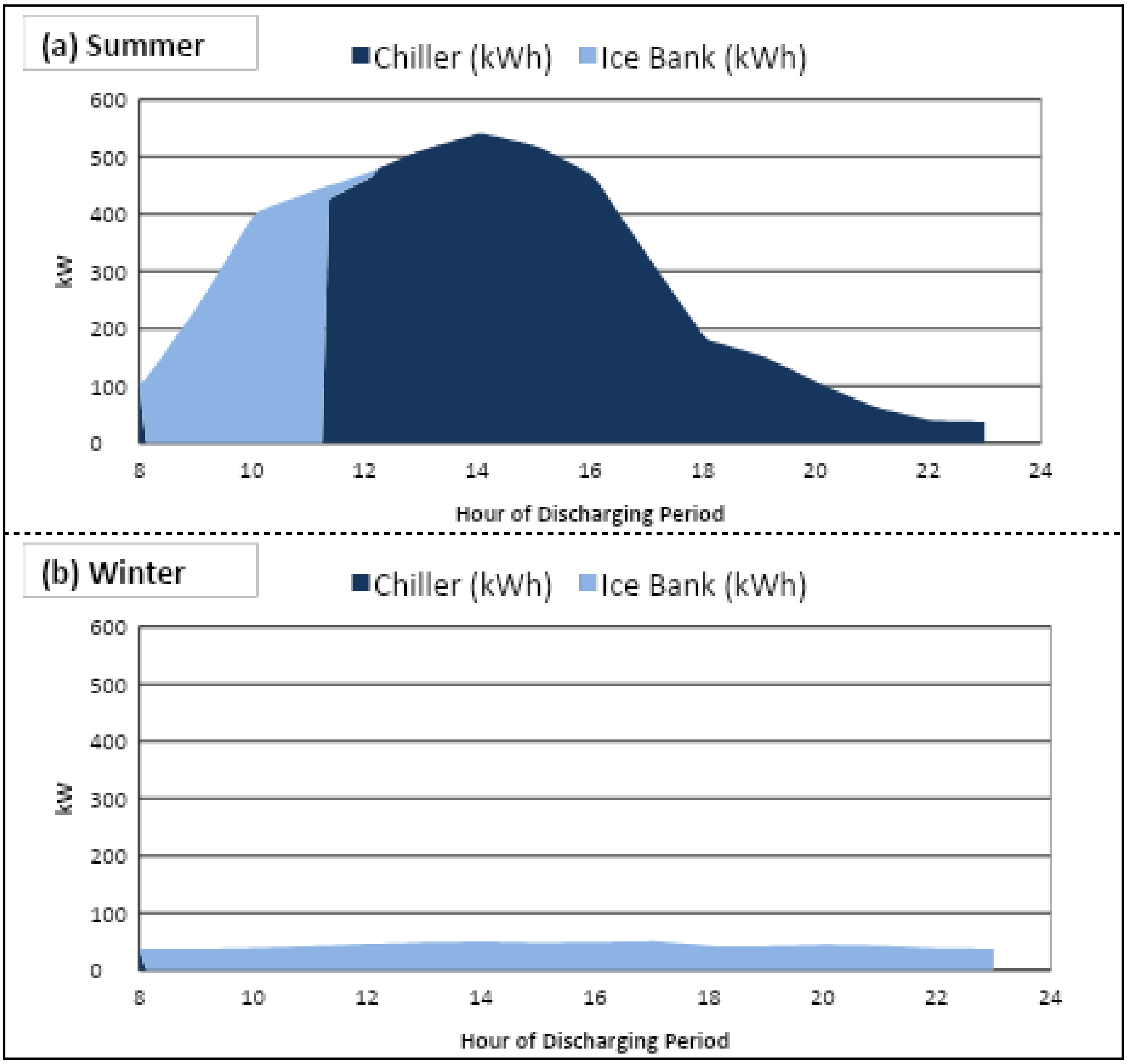


Figure 10-8: Constant proportion discharge control of 100% for (a) summer and (b) winter

10.3.4 Level Chiller

The level chiller discharge control uses the ice bank to minimise the peak cooling load to be met by the chiller. It effectively *levels off* the chiller's cooling load. Figure 10-9 shows the cooling loads provided by the ice bank using level chiller discharge control.

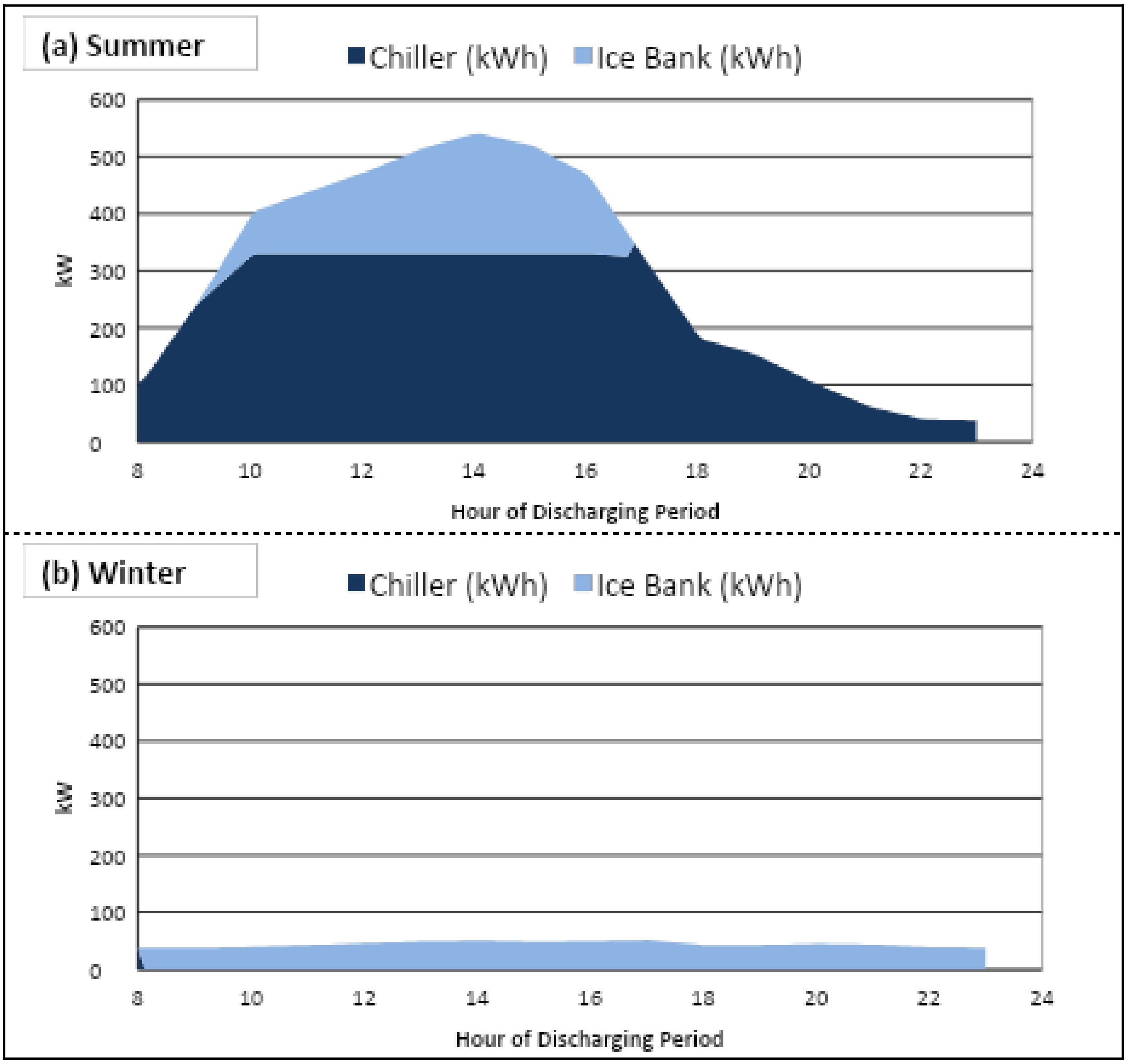


Figure 10-9: Level chiller discharge control for (a) summer and (b) winter

It can be seen from Figure 10-9 that using this control ensures the greatest reduction in peak chiller cooling loads. Similarly to previous discharge controls, if the ice bank has sufficient capacity to provide the cooling for the entire discharge period, the chiller is turned off.

10.4 Optimum Control Analysis

An analysis was carried out to determine the optimum charging and discharging controls using the TRNSYS model. Simulations were carried out for each control option. The optimum control was taken as that which resulted in the minimum annual energy costs for the NGI building.

The charging options; prolonged charge, chiller load dependent charge and ambient air temperature dependent charge are referred to as *Charging #1*, *Charging #2* and *Charging #3* respectively in the analysis. The discharging options; store priority discharge, chiller priority discharge, constant proportion discharge and level chiller discharge are referred to as *Discharging #1*, *Discharging #2*, *Discharging #3 (X)* and *Discharging #4* respectively in the analysis. The *"(X)"* in *Discharging #3* refers to the constant proportion used. Table 10-1 summarises the analysis control references used.

Table 10-1: Ice bank analysis control references

Analysis Reference	Control
Charging #1	Prolonged charge
Charging #2	Chiller load dependent charge
Charging #3	Ambient air temperature dependent charge
Discharging #1	Store priority discharge
Discharging #2	Chiller priority discharge
Discharging #3 (0.25)	Constant proportion discharge, constant proportion of 25%
Discharging #3 (1.00)	Constant proportion discharge, constant proportion of 100%
Discharging #4	Level chiller discharge

10.4.1 Optimum Charge Control

A simulation was run for each of the charging options. All other settings and parameters were kept constant throughout each of the simulations including the discharge option, which was set to store priority discharge. Figure 10-10 shows the total annual energy costs and CO_2 emissions for the NGI building for each of the charging control options. It should be noted that the vertical axes in Figure 10-10 do not start from zero as the differences in annual energy cost and CO_2 emission between the charging options are small in comparison to the annual energy cost and CO_2 emission of the NGI building.

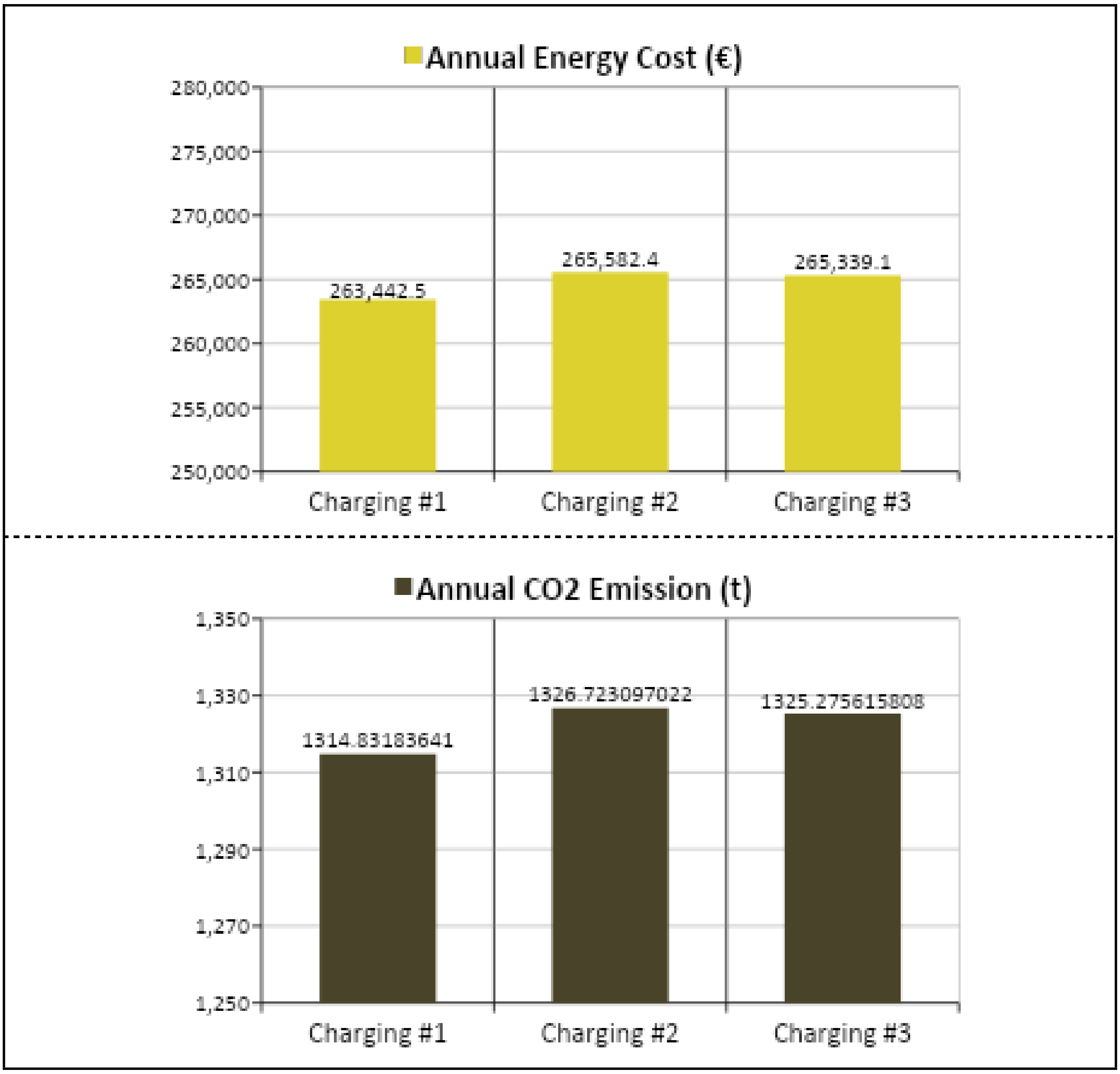


Figure 10-10: Annual energy cost and CO_2 emissions for each ice bank charging option

Figure 10-10 shows that the optimum charging control option is Charging #1, as it has both the minimum annual energy cost and the minimum annual CO_2 emission. The difference in annual energy cost between Charging #1 and Charging #2 is due to the chiller performance in winter. Figure 10-11 shows the chiller performance during winter for Charging #1 and Charging #2. The power consumption of the chiller, the CHW and LTHW loads provided by the chiller, the heat dumped to ambient by the chiller and the COP of the chiller are shown during the charging period.

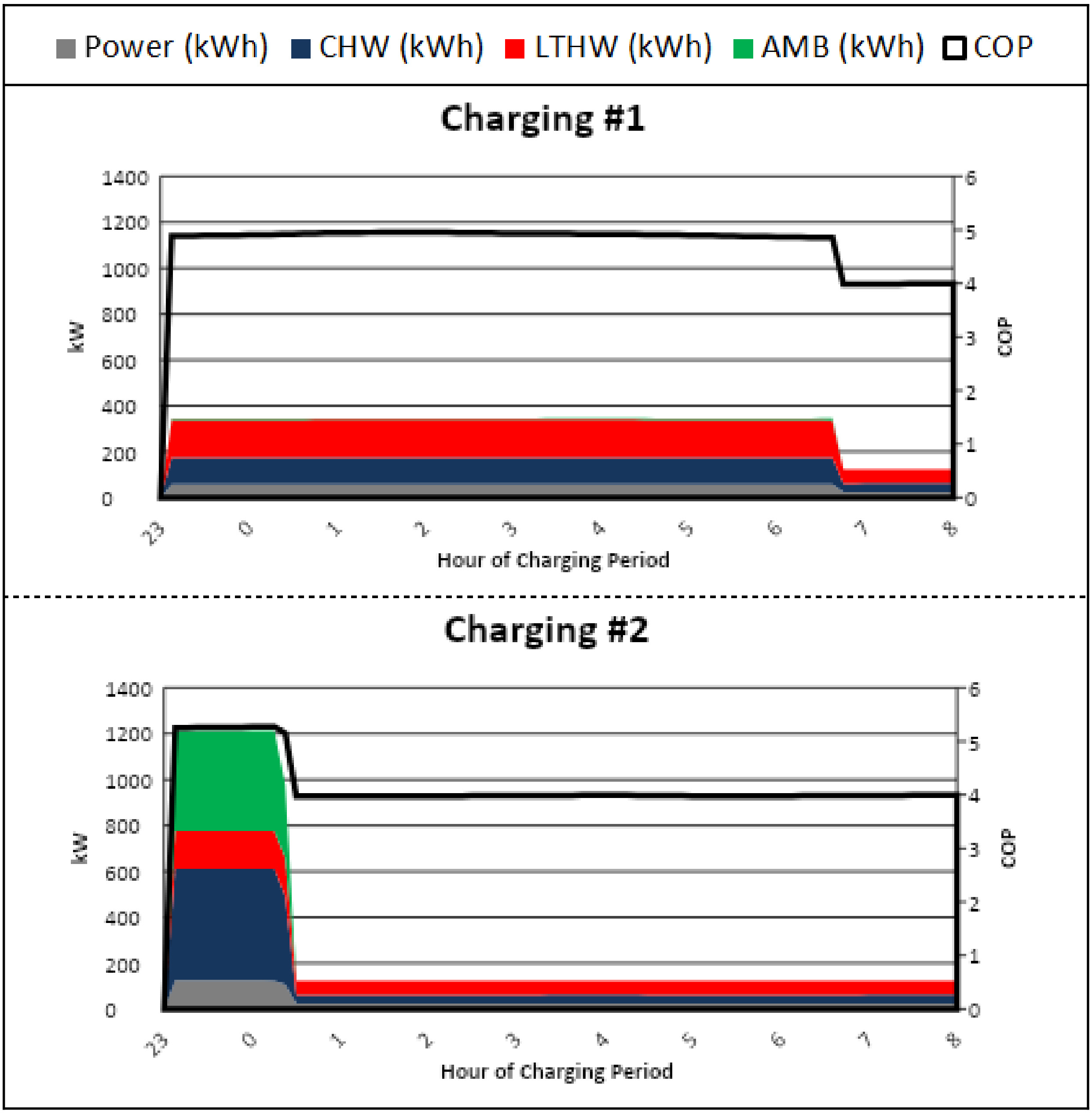


Figure 10-11: Chiller performance during winter for different charging options

The small constant cooling load required by Charging #1 results in a steady chiller COP for the duration of the charging period. It can be seen that almost all of the recoverable heat has been used in Charging #1 and there is little or no heat dumped to ambient.

With Charging #2, the charging load appears as a larger chilled water load over a shorter duration. This has the desired effect of improving the COP of the chiller. However, during this larger charging load, there is insufficient heat load available to accept the recoverable heat. This heat must therefore be dumped to ambient. For the remainder of the day, the chiller provides a smaller cooling load and produces less recoverable heat as a result, even though there is a sufficient heating load available to accept more recoverable heat. This is not generally an issue during the summer months as the available heating load is too small to accept the recoverable heat anyway.

The overall performance of the chiller throughout the year is better for Charging #1 than Charging #2. This is why the annual energy costs and CO_2 emissions for Charging #1 are the lowest. Charging #3 achieves slightly lower annual energy costs and CO_2 emissions than Charging #2 as it shifts the large charging load to the time during the charging period with the lowest ambient air temperature. This improves the COP of the chiller but the issue of dumping recoverable heat during winter remains.

10.4.2 Optimum Discharge Control

A simulation was run for each of the discharging options. As with the charging control analysis, all other settings and parameters were kept constant including the charge option, which was set to prolonged charge.

Figure 10-12 shows the annual energy costs and CO_2 emissions for the NGI building for each of the discharging control options. It can be seen that the order of increasing annual energy costs is equal to the order of increasing annual CO_2 emissions for the discharging controls.

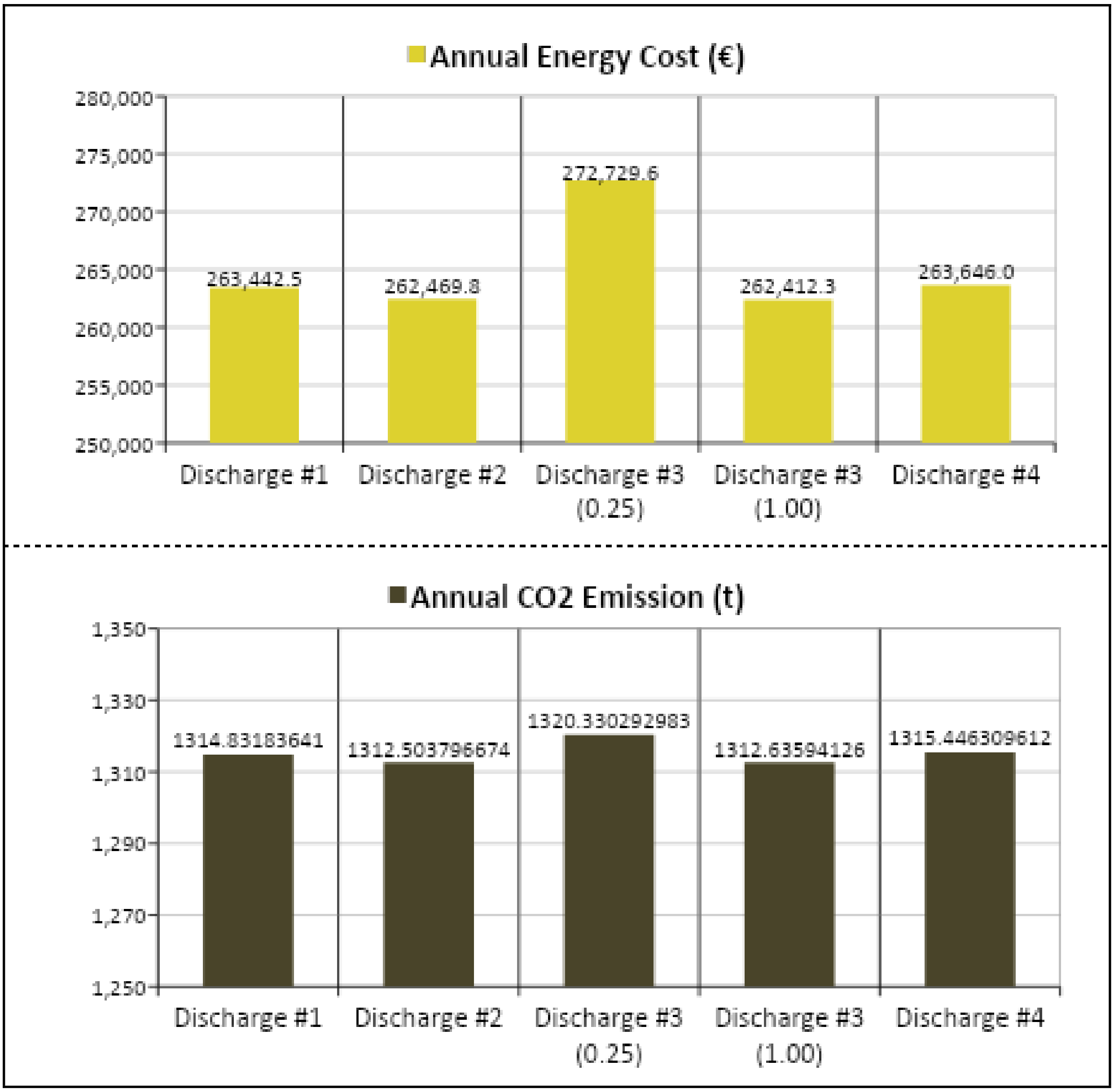


Figure 10-12: Annual energy cost and CO_2 emissions for each ice bank discharging option

The difference in annual energy cost is related to the total annual cooling done by the ice bank and the resultant chiller performance. The chiller performance issues are similar to those mentioned in the optimum charge control analysis. It is affected by the magnitude and timing of the cooling loads resulting from the various discharge options.

The stored cooling available at the beginning of each discharge period is the same for each discharge option. However, the cooling done by the ice bank throughout the year is not the same. Discharge options which require the accurate prediction of the cooling load over the day, may not fully discharge the ice bank by the end of the discharge period. This is due to the complexity of determining how much cooling should be provided by the ice bank at all times. The cooling stored in the ice bank may not be fully utilised when a complex discharge control option is used. Figure 10-13 shows the annual cooling provided by the ice bank for each discharge option.

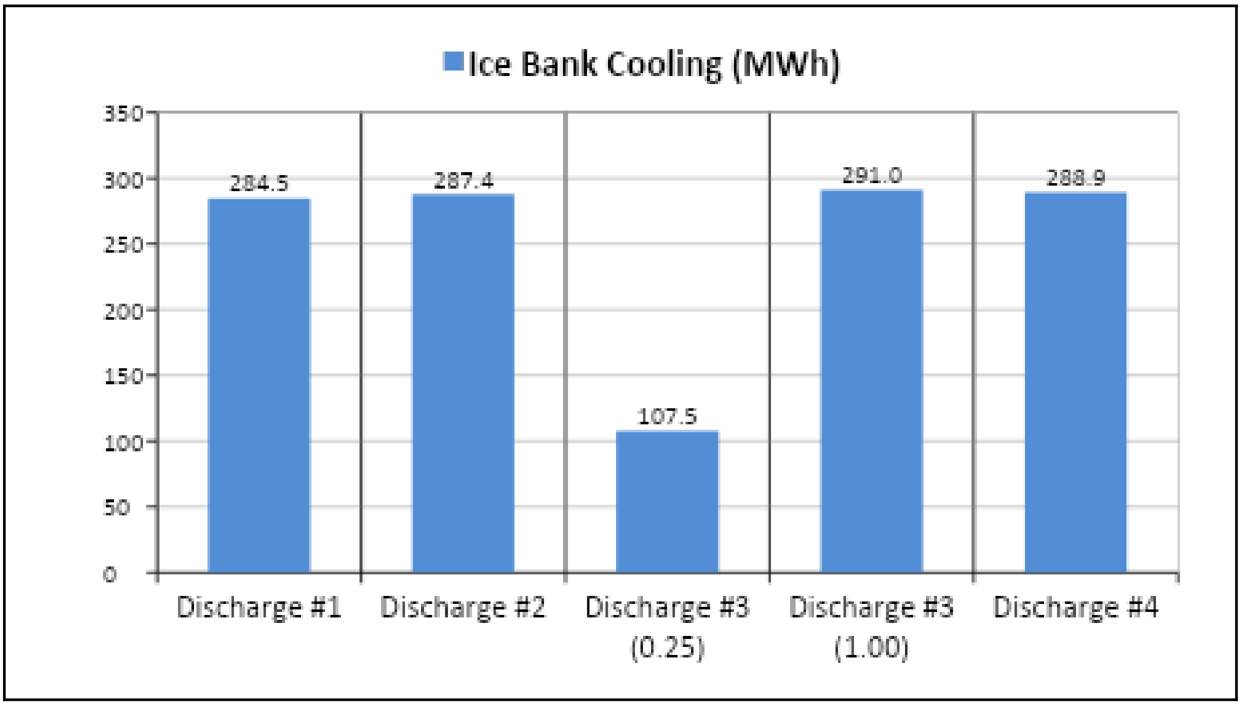


Figure 10-13: Annual ice bank cooling for each ice bank discharging option

Discharge #3 (0.25) provides the least amount of cooling from the ice bank over the year. This is not due to the complexity of the control. It is simply because the ice bank is only assigned 25% of the cooling load. Discharge #3 (1.00) provides the most amount of cooling over the year. Again, this is due to the simplicity of the control. The ice bank simply provides all of the cooling until it is depleted. This ensures all of the stored cooling is used by the end of the discharge period.

Discharge #1, Discharge #2 and Discharge #4 provide varying annual amounts of cooling from the ice bank. If their discharge control perfectly predicted the cooling loads over the discharge period and assigned the correct corresponding ice bank cooling loads, the annual cooling load provided by the ice bank would equal that of Discharge #3 (1.00).

A cost which is not considered in this analysis is the charge for exceeding the agreed MIC, which can be significant. The MIC is most likely to be exceeded during summer when the increased chiller power consumption adds to the existing building electrical demand. A benefit therefore exists in choosing a discharge option which reduces the peak chiller power consumption and so reduces the likelihood of exceeding the MIC.

The difference in annual energy cost and CO_2 emission between Discharge #2 and Discharge #3 (1.00) is very small. Discharge #2 has the added benefit over Discharge #3 (1.00) of reducing the peak chiller electrical load somewhat. Therefore Discharge #2 was considered the optimum discharge control.

10.4.3 Optimum Ice Bank Control Philosophy

The optimum ice bank control philosophy for the NGI building was determined to be a combination of prolonged charge control and chiller priority control. This combination results in the lowest annual energy cost and CO_2 emission while providing some reduction to the peak chiller electrical demand.

11 Air Source Heat Pump Operation

This chapter addresses the third thesis objective of determining when the ASHP should operate. Figure 11-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

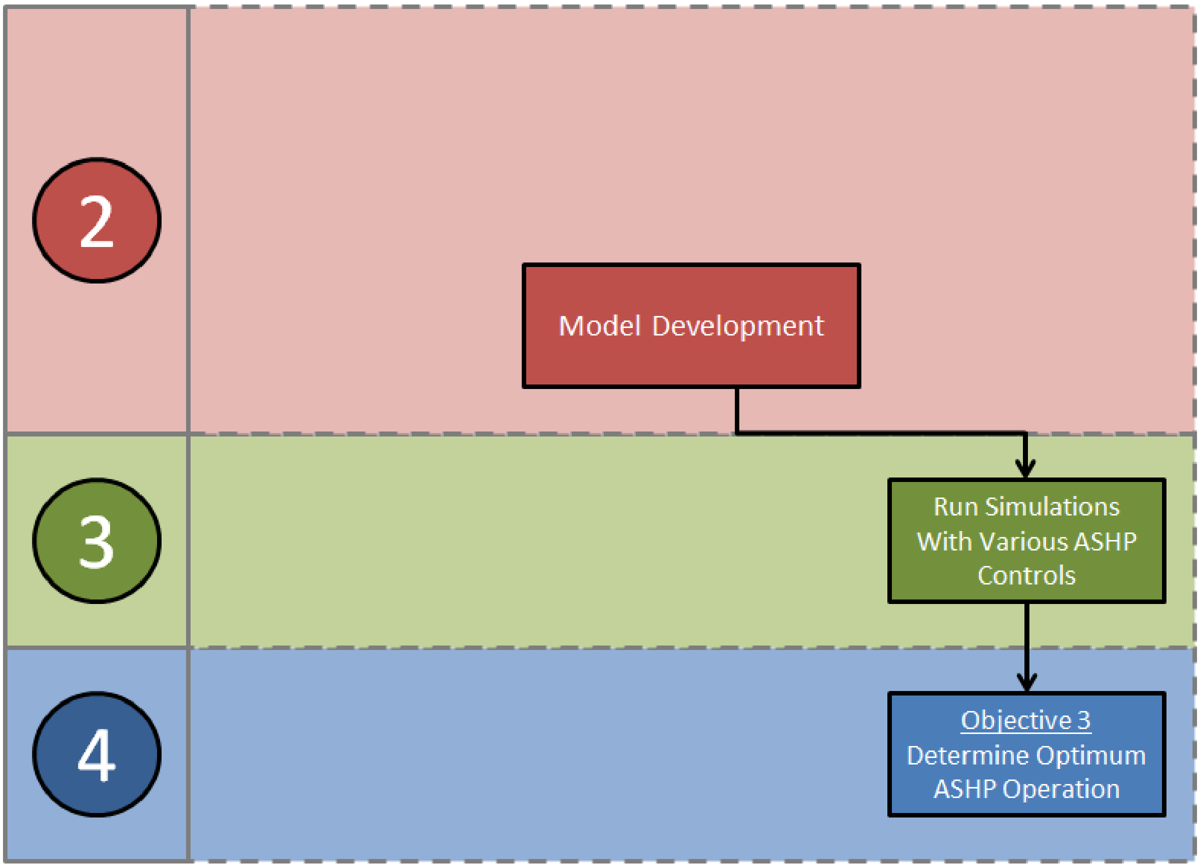


Figure 11-1: Chapter 11 process diagram tasks

11.1 Introduction

The chiller is capable of operating as an air source heat pump. Two new operating modes become available when the chiller is allowed to operate as an ASHP; heating only mode and heating main mode. In heating main mode, there is no cooling load available so the chiller only provides a heating load. In heating main mode, there is a relatively small cooling load available so the chiller provides mostly heating while satisfying the entire cooling load.

11.2 Frequency of ASHP Operation

Simulations were run with the ASHP enabled at all times and without the ASHP enabled to determine the frequency of each chiller operating mode. The CHP unit and ice bank were enabled in the simulations and controlled by their respective optimum control philosophies. The frequencies of each chiller operating mode when the ASHP is disabled and enabled are shown in Figure 11-2.

When the ASHP is disabled, the chiller is off for approximately half of the year. This is because the chiller is off during the daytime in the heating season as the ice bank provides all of the cooling. If the ASHP is enabled, the chiller operates in heating only mode during this time.

The decrease in the amount of time the chiller is off when the ASHP is enabled corresponds directly to the amount of time the chiller operates in heating only mode. The slight decrease in the amount of time the chiller operates in total recovery mode when the ASHP is enabled corresponds directly to the amount of time the chiller operates in heating main mode. The amount of time the chiller operates in cooling only mode or cooling main mode remains unchanged when the ASHP is enabled.

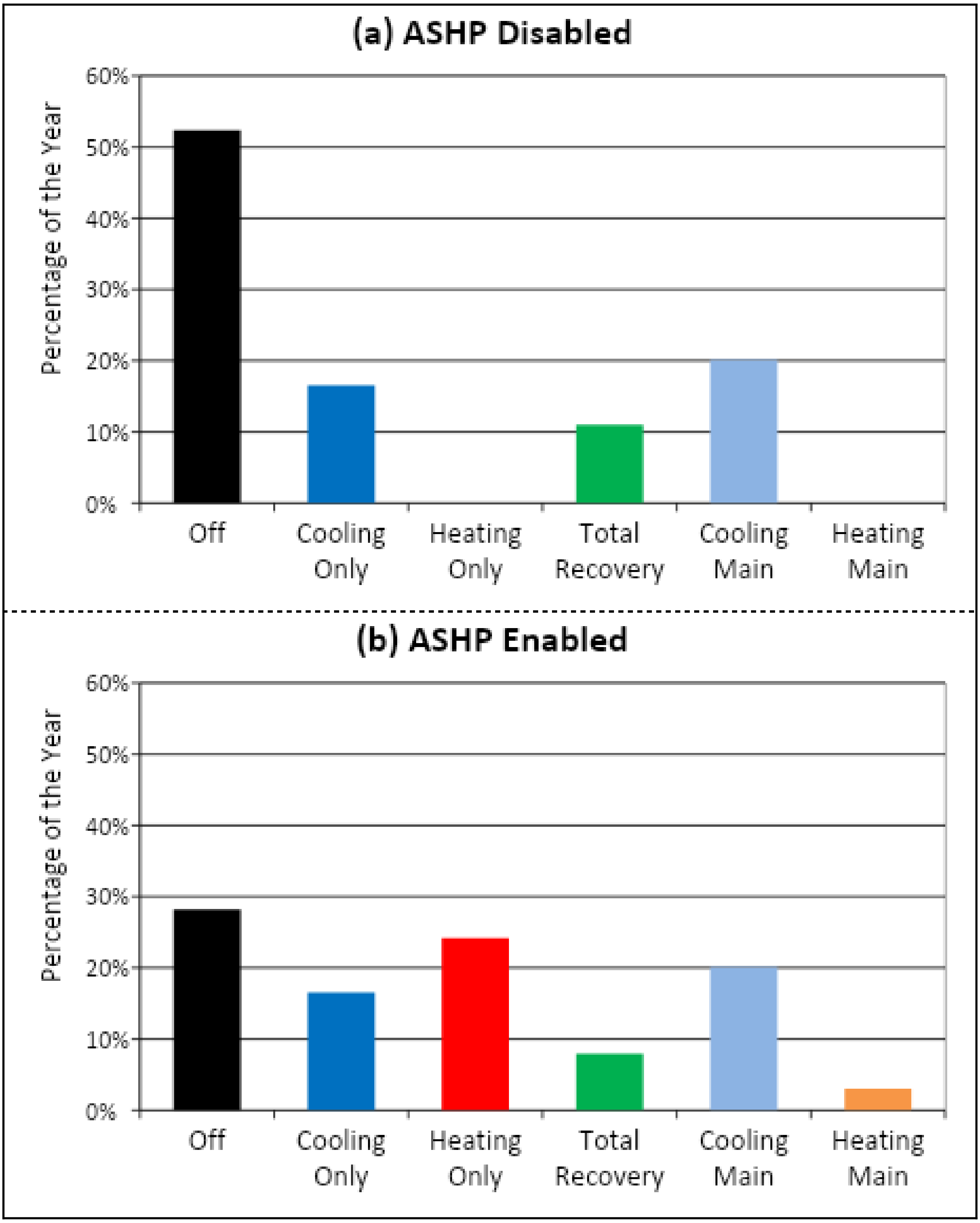


Figure 11-2: Chiller operating mode frequencies for a (a) disabled and (b) enabled ASHP operation

11.3 Day & Night ASHP Operation

It is more beneficial to operate the ASHP during night time due to the reduced grid electrical tariffs and the lower ambient air temperatures. Figure 11-3 shows the number of hours that the chiller operates in heating only mode or heating main mode during day and night times. It can be seen that the chiller operates in heating only mode much more often than it operates in heating main mode. However, the chiller always operates in heating only mode during the daytime. This is because the only time the chiller does not have to provide a cooling load is during the daytime in the heating season when the ice bank provides all of the cooling. By contrast, the chiller operates in heating main mode predominantly during night time. This mode mostly occurs in the heating season when the NGI cooling load and ice bank charging load are relatively small.

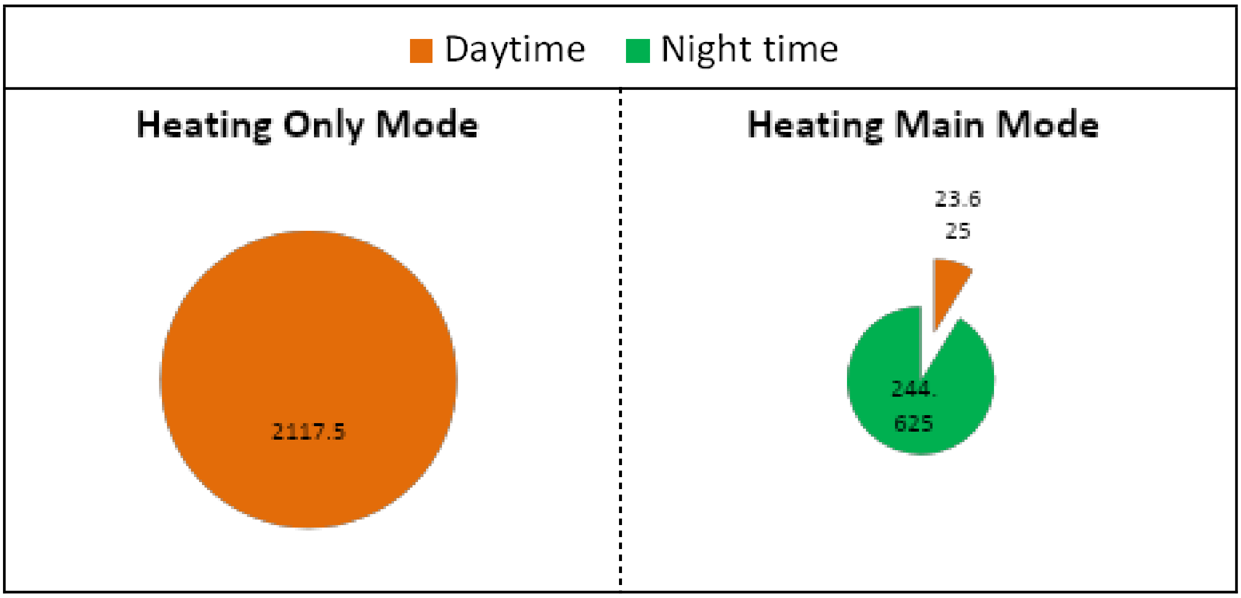


Figure 11-3: Day and night time occurrence of chiller heating modes

11.4 Heating Source: ASHP or Boiler?

The heating provided by the CHP unit remains constant regardless of the ASHP settings. This is because the CHP unit's heat is given priority over the chiller's heat. The same total amount of heat must therefore be provided by the chiller and boiler in all scenarios. If the ASHP is used as a heating source, it displaces some of the heating provided by the boiler.

To provide an indication of which heating source should be used in which circumstance, the average efficiency of the boiler and the average COPs of the ASHP in each heating mode were used. The use of average COPs only provides an indication of when the ASHP should operate. The actual COP of the ASHP depends on the ambient air temperature and its PLR. Simulations must be run to confirm when the ASHP should operate. This is done in section 11.5.

The average COPs of the ASHP were calculated using data from the simulation used in the previous section which had the ASHP enabled. These values are given in Table 11-1. The ASHP only operated in heating only mode during the day so a single average COP was sufficient for this mode. The gas and grid electricity costs and CO_2 intensities used are reiterated in Table 11-2.

Table 11-1: Average boiler efficiency and ASHP COPs

Heating Source	Average Efficiency (%) or COP (W/W)
Boiler	91%
ASHP – heating only mode	2.38
ASHP – heating main mode (daytime)	3.11
ASHP – heating main mode (night time)	3.41

Table 11-2: Fuel cost & CO_2 intensities for ASHP analysis

Fuel	Cost (€/kWh)	CO_2 Intensity (kg/kWh)
Gas	0.035	0.206
Grid Electricity (Day)	0.160	0.414
Grid Electricity (Night)	0.080	0.490

11.4.1 Relative Heating Costs & CO_2 Emissions

One method of indicating which heating source should be used is to examine the relative heating costs and CO_2 emissions of each source. The values from Table

11-1 and Table 11-2 were used to determine the relative heating cost and CO_2 emissions of each heating source. The resulting figures are shown in Figure 11-4.

It can be seen that the ASHP's heating only mode is the most expensive source of heating. The ASHP's heating main mode is not as expensive as its heating only mode because the cost is offset by the cooling provided. The ASHP's heating main mode is much cheaper at night time when the grid electricity tariffs are low. The ASHP's heating main mode at night is the only time that the ASHP is cheaper at providing heat than the boiler. If the ASHP operated in heating only mode during the night, the heating cost would be approximately half of that during the day. The ASHP's heating only mode would therefore be viable at night time if suitable loads during this time existed.

Unlike the annual energy costs, the annual CO_2 emissions of providing heat from the ASHP are lower than those from providing heat from the boiler. This is because the cost of grid electricity during the day is approximately 4.6 times the cost of gas whereas the CO_2 intensity of grid electricity is only approximately twice that of gas. The heating CO_2 emissions of the ASHP's heating main mode are lower during the day than the night due to the higher CO_2 intensity of grid electricity at night.

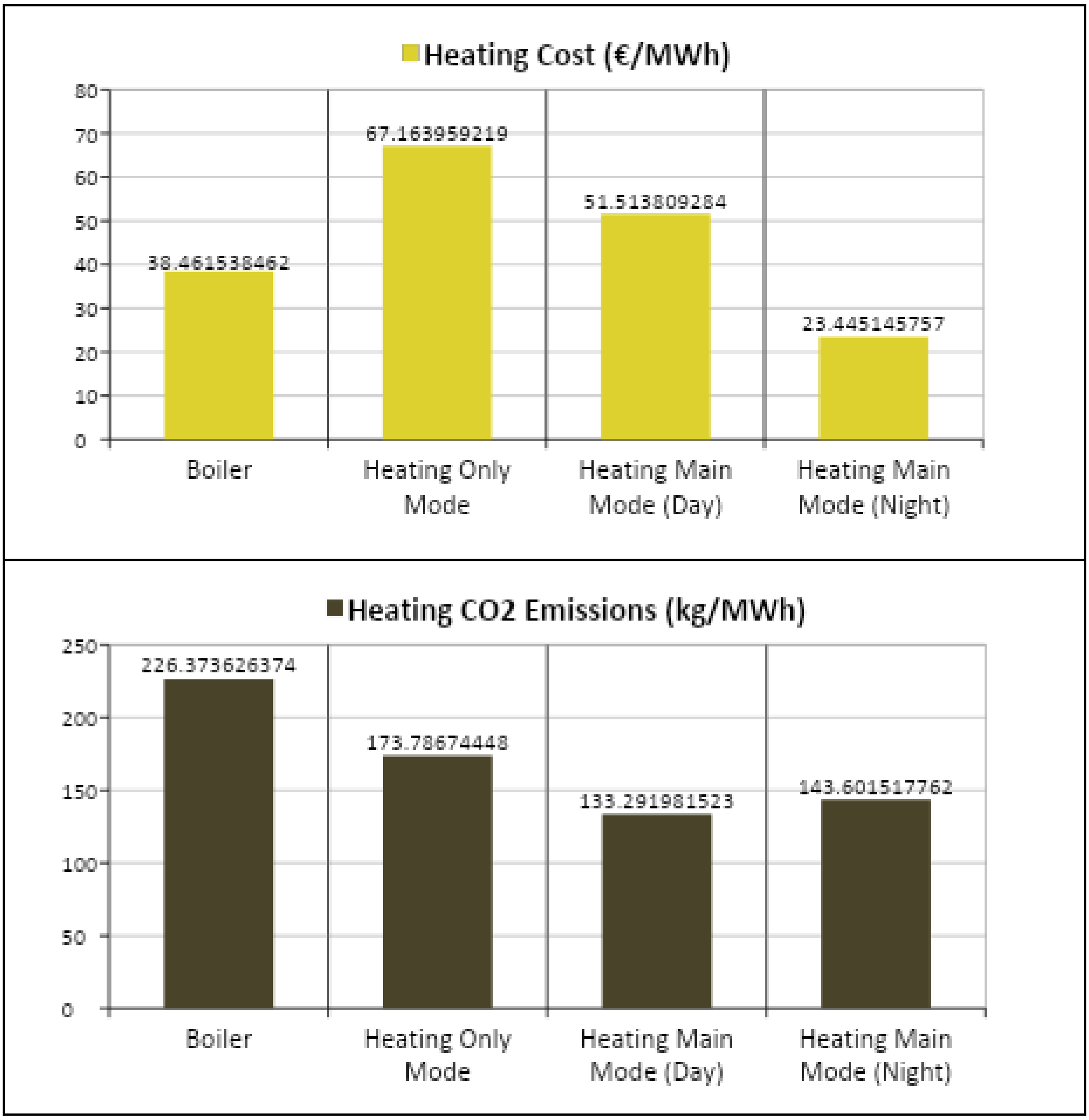


Figure 11-4: Heating cost and CO_2 emission by heating source

11.4.2 Breakeven Chiller COPs

An alternative approach to indicate which heating source should be used in which circumstance is to determine the breakeven COPs for energy cost and CO_2 emission. The breakeven COP for energy cost is the COP that must be achieved so that the ASHP will provide a given heating load, at a lower cost than the boiler. The breakeven COP for CO_2 emission is the COP that must be achieved by the ASHP so that the ASHP will provide a given heating load, with less CO_2 emissions than the boiler.

The breakeven COP for energy cost is higher during the day than the night due to the higher grid electricity tariff during the daytime. The breakeven COP for CO_2 emission is lower during the day than the night due to the higher CO_2 intensity during the daytime.

Figure 11-5 shows the COPs achieved by the ASHP in heating only mode, in heating main mode during the day and in heating main mode during the night. It also shows the breakeven COPs for daytime and night time which must be achieved for the ASHP to; (a) provide an energy cost saving over the boiler and (b) provide a CO_2 emission saving over the boiler. The average day and night COPs for heating main mode should only be compared against the respective breakeven COPs whereas the average COP for heating only mode should only be compared against the daytime breakeven COP.

It can be seen from Figure 11-5 that the only ASHP operation mode to provide an energy cost saving over the boiler is heating main mode during night time. It can also be seen that all of the ASHP operating modes provide a CO_2 emission saving over the boiler regardless of the time of day.

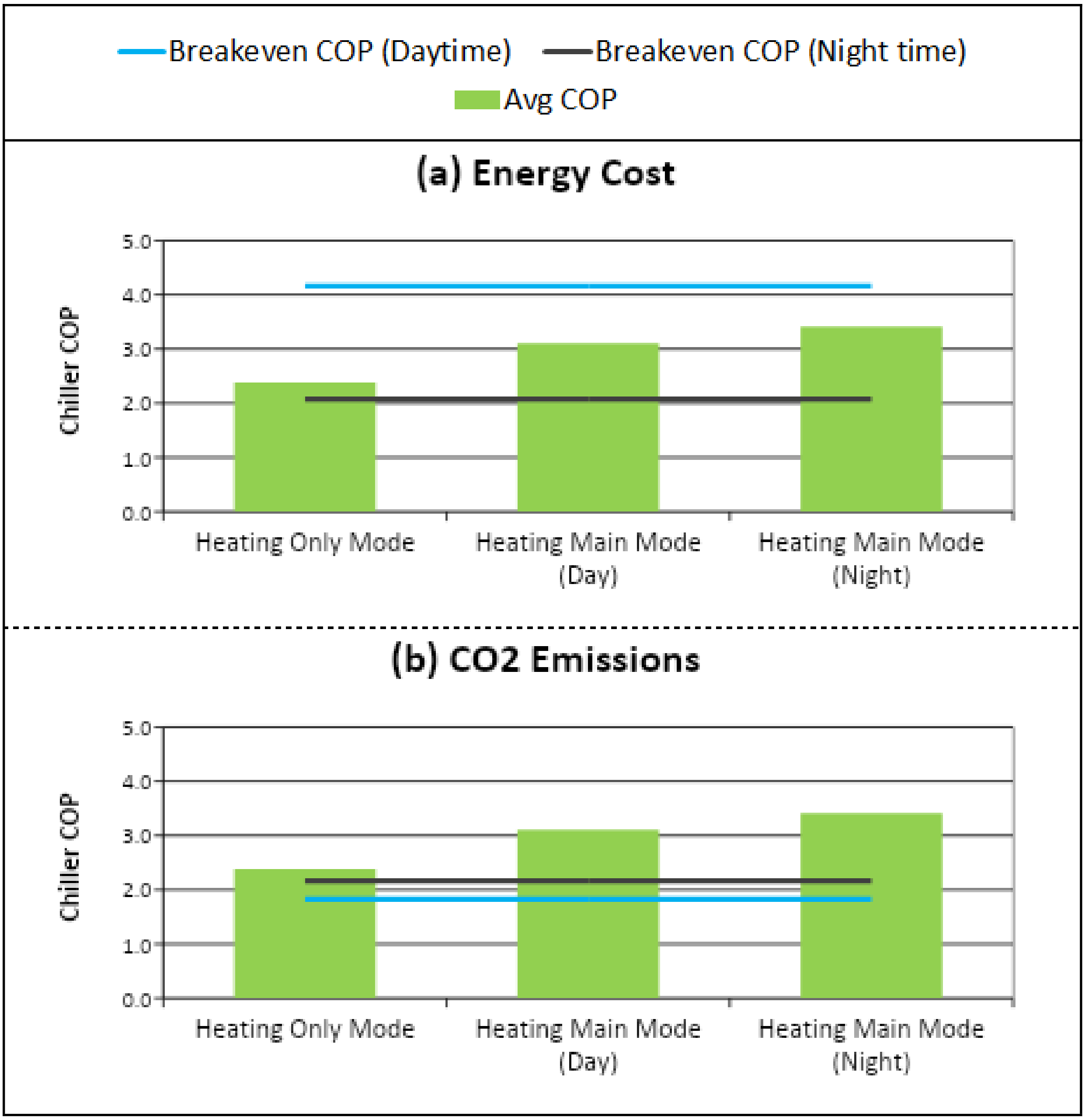


Figure 11-5: Breakeven chiller COP for (a) energy cost and (b) CO_2 emission for daytime and night time

11.4.3 ASHP Heating

Both of the methods used to indicate when the ASHP should be used ahead of the boiler to provide heating reach the same conclusions. The ASHP should only operate during night time if the annual energy costs are to be minimised. The ASHP should operate at all times if the annual CO_2 emissions are to be minimised.

11.5 ASHP Simulation Analysis

Three simulations were run to confirm when the ASHP should operate. The first simulation never enabled the ASHP. The second simulation always enabled the ASHP. The third simulation only enabled the ASHP at night. Figure 11-6 compares the annual energy costs and CO_2 emissions resulting from the three simulations.

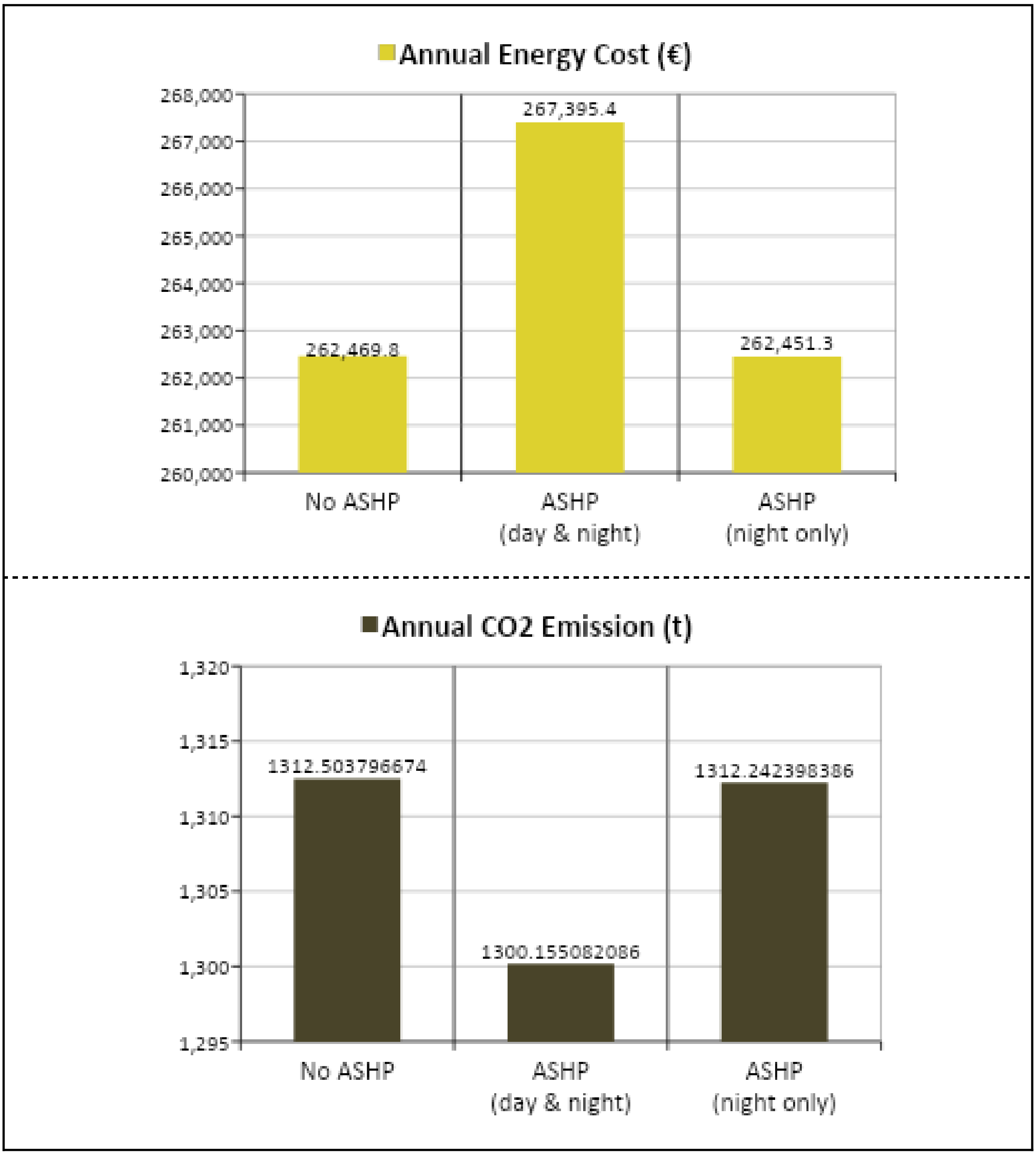


Figure 11-6: Annual energy costs and CO_2 emissions for ASHP analysis simulations

It can be seen from Figure 11-6 that enabling the ASHP at all times increases the annual energy cost but decreases the annual CO_2 emissions compared to the case with no ASHP operation. When the ASHP is enabled during night time only, both the annual energy cost and CO_2 emissions are reduced. However, the reduction is very small as there are only 245 hours of night time ASHP operation throughout the year.

The changes in annual energy costs and CO_2 emissions are due to the changes in heating provided by the chiller and boiler. Figure 11-7 shows the annual heating provided by the boiler and ASHP for each of the scenarios analysed. It can be seen that much more heat is provided by the chiller when the ASHP is enabled at all times compared to when the ASHP is only enabled at night time. This is due again to the limited operation of the ASHP at night.

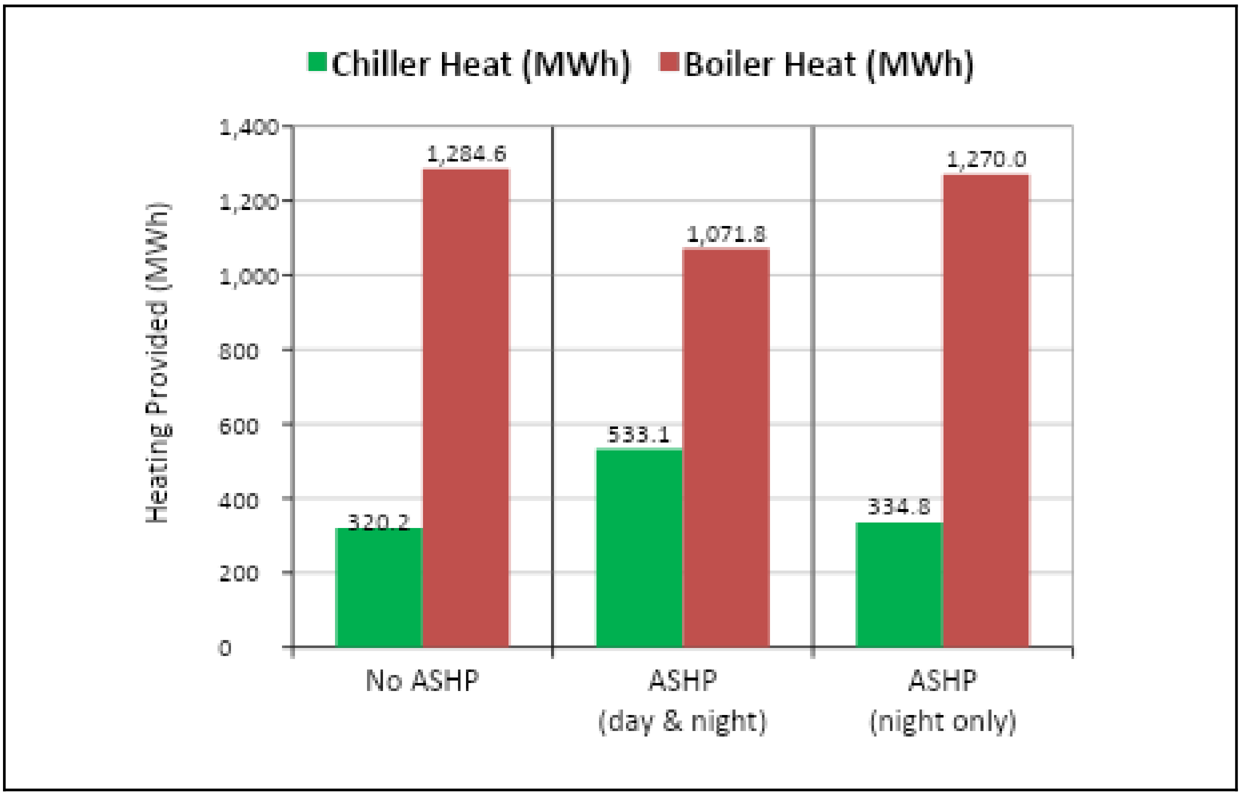


Figure 11-7: Annual heating provided by the chiller and the boiler for various ASHP settings

11.6 ASHP Operation Conclusion

The simulation results confirm the findings found in the previous sections of this chapter:

- The chiller rarely operates as an ASHP during night time even when it is enabled.
- Any heat that is provided by the ASHP displaces heat provided by the boilers.
- To minimise annual energy costs
    - The ASHP should only operate during off peak electrical hours (night time)
- To minimise CO_2 emissions
    - The ASHP should operate at all times regardless of the grid electrical tariffs

These results are only applicable to the energy costs and CO_2 intensities provided in Table 11-2. If the energy cost gap between daytime grid electricity and gas is reduced, it may make the ASHP more economical than the boiler.

12 Compatibility of Low Energy Technologies

This chapter addresses the final thesis objective of determining the compatibility of the NGI's low energy plant items. The inclusion of each of the low energy plant alternatives in BDP's design is also justified at the end of this chapter.

The optimum control philosophies for the CHP unit, ice bank and heat recovery chiller had to be determined before the simulations could be run for the final thesis objective. Figure 12-1 highlights the relevant tasks from the simplified process diagram that are addressed in this chapter.

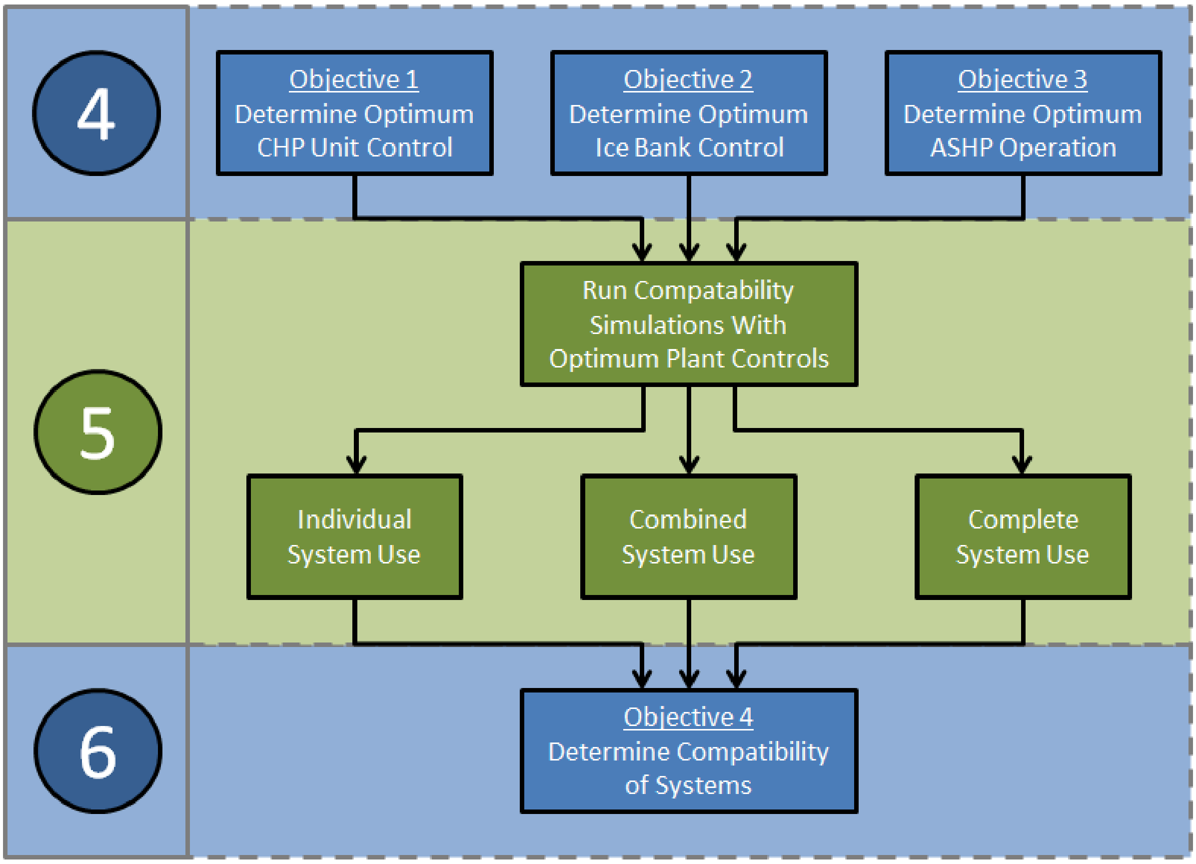


Figure 12-1: Chapter 12 process diagram tasks

12.1 Introduction

The use of the CHP unit, the ice bank and the heat recovery chiller influence the annual energy costs and CO_2 emissions of a building. These plant items may provide certain savings when used individually but different savings when used in combination with each other.

Various combinations of the CHP unit, the ice bank and the heat recovery chiller were simulated using the TRNSYS model for use in the NGI building. Energy costs and CO_2 emissions were quantified for each combination and compared to a *basic* case. The basic case provided all of its cooling from a conventional chiller, all of its heating from natural gas boilers of 91% efficiency and imported all of its electricity from the grid. A conventional chiller was selected in the TRNSYS model by disabling the heat recovery feature of the chiller component and the CHP unit and ice bank components were simply switched off.

Eight simulations were required to examine each combination of the three systems. The same NGI heating, cooling and electrical loads were used for each simulation. The following settings were applied to each plant item when in use:

- CHP unit settings:
  - *Minimum Cost* control philosophy used and CHP heat given priority over chiller heat at all times
  - Two winter weeks and two summer weeks of downtime applied due to maintenance
  - Maintenance costs not accounted for in annual savings
- Ice Bank settings:
  - *Prolonged Charge* & *Chiller Priority* control philosophies used
  - Charging period between 23:00 and 08:00.
- Heat Recovery Chiller settings:
  - ASHP operation only enabled during off peak electrical tariffs (i.e. night time operation only).

The following sections analyse the resulting data from the simulation of the individual use of the plant items, the combined use of the plant items and the complete use of the plant items.

12.2 Individual Use of Plant

The CHP unit, ice bank and heat recovery chiller were simulated individually and compared against the Basic case. These three simulations were labelled *CHP, IB* and *HR* respectively.

Figure 12-2 shows the annual energy cost savings & annual CO_2 emission savings of the three systems compared to the Basic case. Figure 12-3 shows the annual gas savings & annual grid electricity savings of the three systems compared to the Basic case. A negative saving represents an increase.

Each simulation is discussed in relation to Figure 12-2 and Figure 12-3 in the following sections.

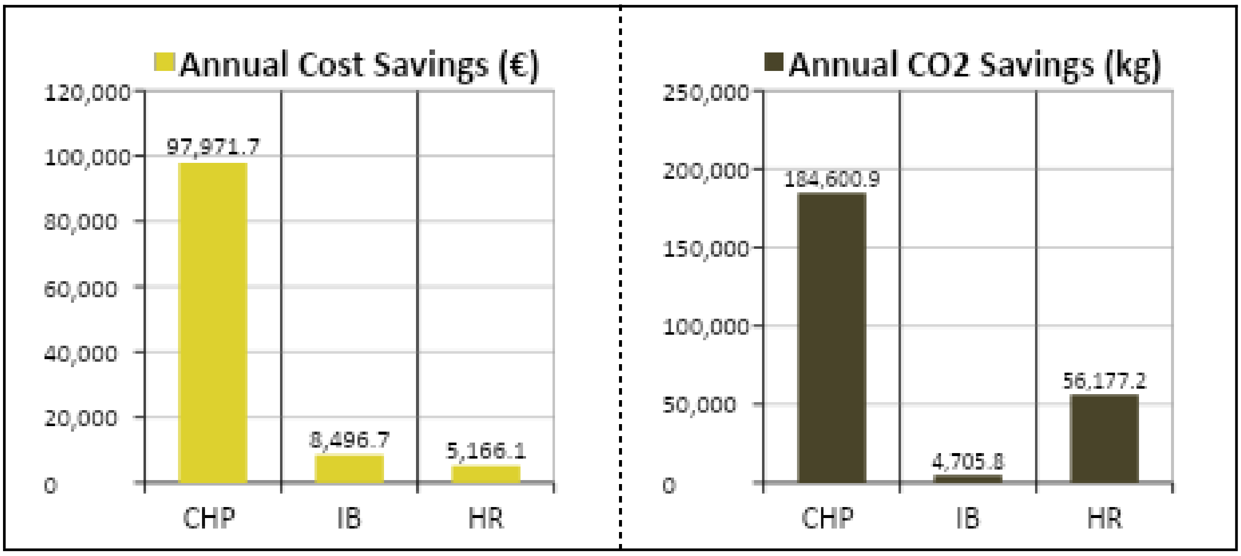


Figure 12-2: Annual energy cost & CO_2 savings from individual plant items

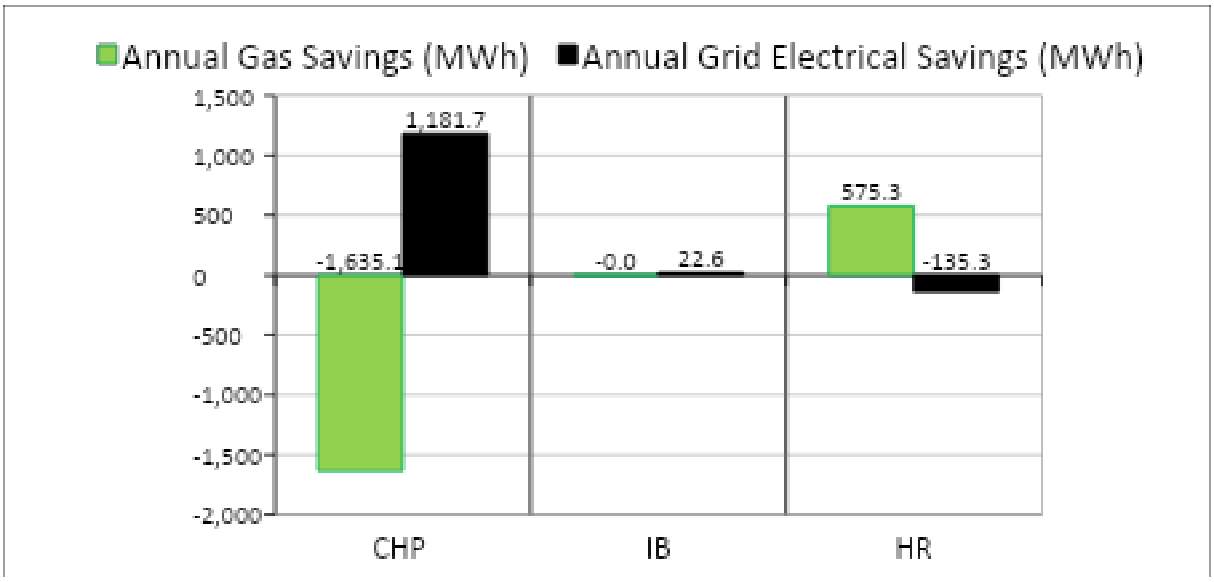


Figure 12-3: Annual gas & grid electricity savings from individual plant items

12.2.1 CHP

The CHP unit provides both the highest annual energy cost saving and highest annual CO_2 emission saving of the three systems. Energy cost and CO_2 emission savings of approximately €98,000 and 185,000kg respectively are achieved.

The CHP unit uses much more gas than the Basic case. However, the CHP unit uses this gas to provide both power and heat resulting in much less grid electricity being required. The gas which displaces this grid electricity is both cheaper and less CO_2 intensive. This is how the CHP unit achieves such massive savings.

12.2.2 IB

The ice bank achieves energy cost and CO_2 emission savings of approximately €8,500 and 4,700kg respectively. The ice bank system has no effect on the gas consumption of the NGI building.

The ice bank shifts the building's cooling load from daytime to night time. The chiller must therefore provide an increased cooling load at night and smaller cooling load or no cooling load during the day. The corresponding chiller electrical load also shifts from daytime, when electricity prices are high, to night time, when electricity prices are low. An additional benefit is that the chiller can provide the cooling load more efficiently due to colder ambient air temperatures at night and an increased part load ratio from the charging load.

Energy cost and CO_2 savings are achieved by the ice bank as less grid electricity is required and more of the grid electricity used is imported at night when the electricity price is relatively low. The CO_2 savings are not as significant as the energy cost savings due to the higher CO_2 intensity of grid electricity at night.

12.2.3 HR

The heat recovery chiller achieves energy cost and CO_2 emission savings of approximately €5,200 and 56,200kg respectively. The gas consumption of the NGI is reduced as the chiller provides heat that would otherwise be provided by boilers.

The chiller provides heating and cooling from the same process. The temperature lift required by the chiller in heat recovery mode is greater than that required in cooling only mode. This larger temperature lift requires the chiller to work harder and the electrical consumption of the chiller increases as a result. However, the COP of the chiller increases as it provides both heating and cooling from the same electrical input.

Energy cost and CO_2 savings are achieved as the savings in gas consumption are much greater than the increase in grid electricity consumption. However, both energy cost and CO_2 savings are diminished as cheaper, less CO_2 intensive gas is displaced by more expensive and more CO_2 intensive grid electricity

12.3 Combined Use of Plant

Each possible combination of the CHP unit, ice bank and heat recovery chiller was simulated. The savings from the corresponding individual cases were summed together and compared against the savings from each combination. This method was used to determine whether the combined plant items had an effect on the energy cost and CO_2 savings achieved by the individual plant items throughout the year.

The simulations were labelled according to the systems enabled in them. For example, the simulation with the combination of the CHP unit and heat recovery chiller was labelled *CHP & HR* and compared against the sum of the individual savings achieved by *CHP* and *HR*, labelled *Σ(CHP+HR).*

12.3.1 CHP & IB

The CHP unit and ice bank are fully compatible with each other. Both systems have no effect on the energy cost and CO_2 savings achieved by the other system. Their savings are simply summed together when both systems are used.

The CHP unit was sized to meet the base electrical load of the NGI building. The CHP unit can therefore operate at full output even overnight, once there is a heating load available. If the NGI electrical load dropped below the maximum output of the CHP unit at night, the increased chiller electrical load at night caused by the ice bank would allow the CHP unit to increase its output. However, this is not the case and the two systems have no effect on each other as a result.

Figure 12-4 and Figure 12-5 show the summed savings of the individual CHP and IB systems, labelled *Σ(CHP+IB)*, compared to the savings of the combined CHP and IB systems, labelled *CHP & IB*.

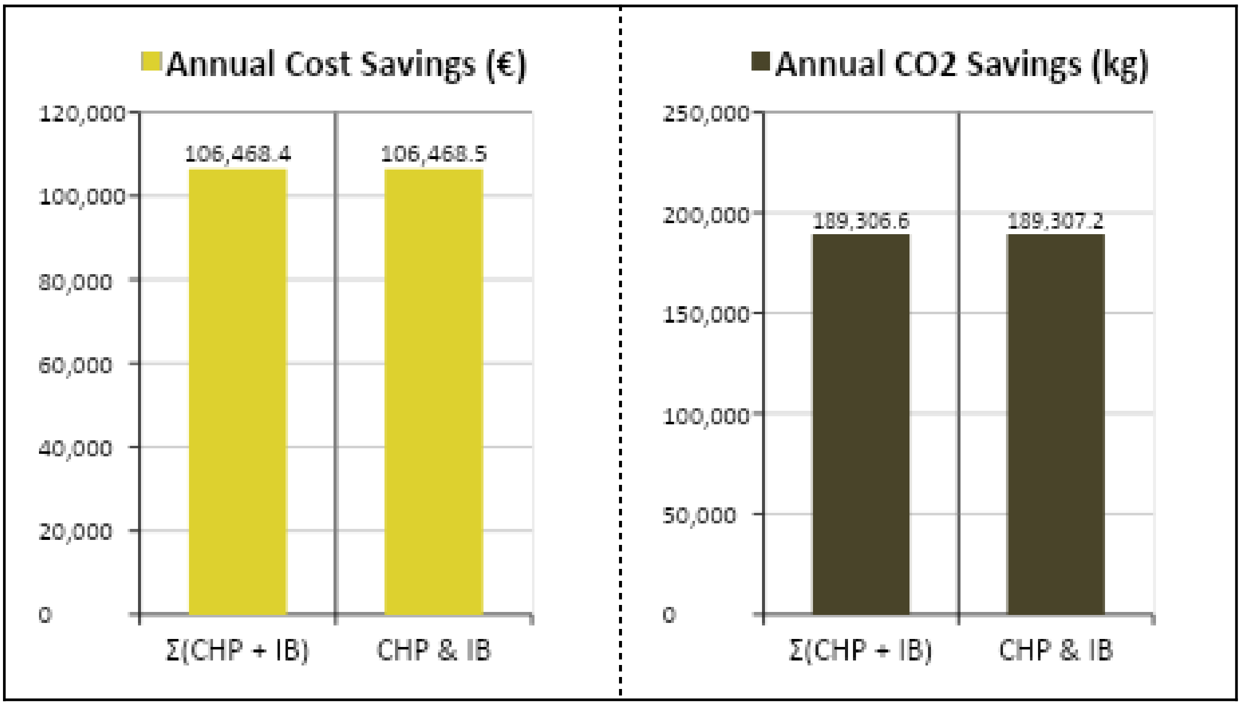


Figure 12-4: Annual energy cost & CO_2 emission savings from individual and combined CHP and IB plant

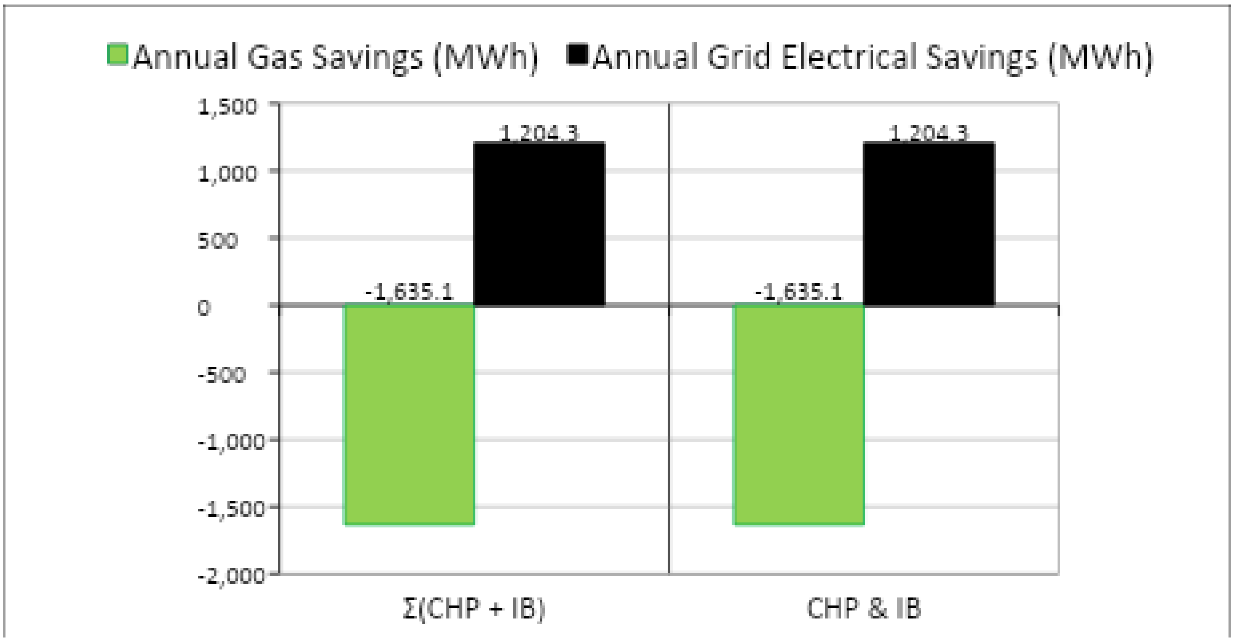


Figure 12-5: Annual gas & grid electricity savings from individual and combined CHP and IB plant

12.3.2 CHP & HR

The CHP unit and heat recovery chiller are not fully compatible. The sum of the energy cost and CO_2 emission savings achieved by each of the individual systems is greater than the savings achieved by the combination of the systems as shown in Figure 12-6. Figure 12-7 shows that the combined systems use less grid electricity and more gas than the sum of the individual systems.

The CHP unit and heat recovery chiller compete for the same heating load. If the CHP unit provides enough heat to satisfy the higher temperature heating load, the remainder of the heat is used to provide the lower temperature heating load. In this case, the chiller can only provide any lower temperature heating load that hasn't been provided by the CHP unit. The CHP unit effectively *steals* the heating load from the chiller. Generally this is not an issue in winter when there are sufficient heating loads available for both the CHP unit and the heat recovery chiller. However, during summer, the chiller may have to revert to cooling only mode if the CHP unit has provided the entire lower temperature heating load.

There are more grid electricity savings when both of the systems are used as the chiller operates in cooling only mode more frequently. In cooling only mode, the electrical consumption of the chiller reduces due to the lower temperature lift required. However, the COP of the chiller also reduces as only cooling is provided by the chiller instead of both heating and cooling. The gas consumption savings are reduced when both of the systems are used as the chiller provides less heat than when it is used on its own.

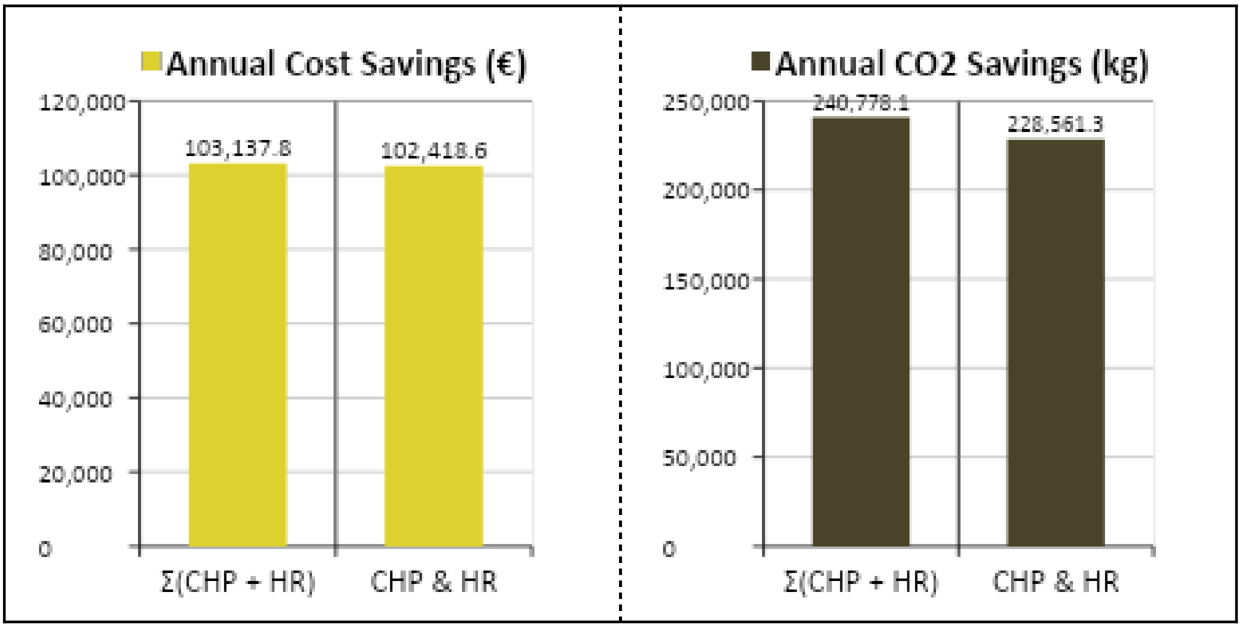


Figure 12-6: Annual energy cost & CO_2 emission savings from individual and combined CHP and HR plant

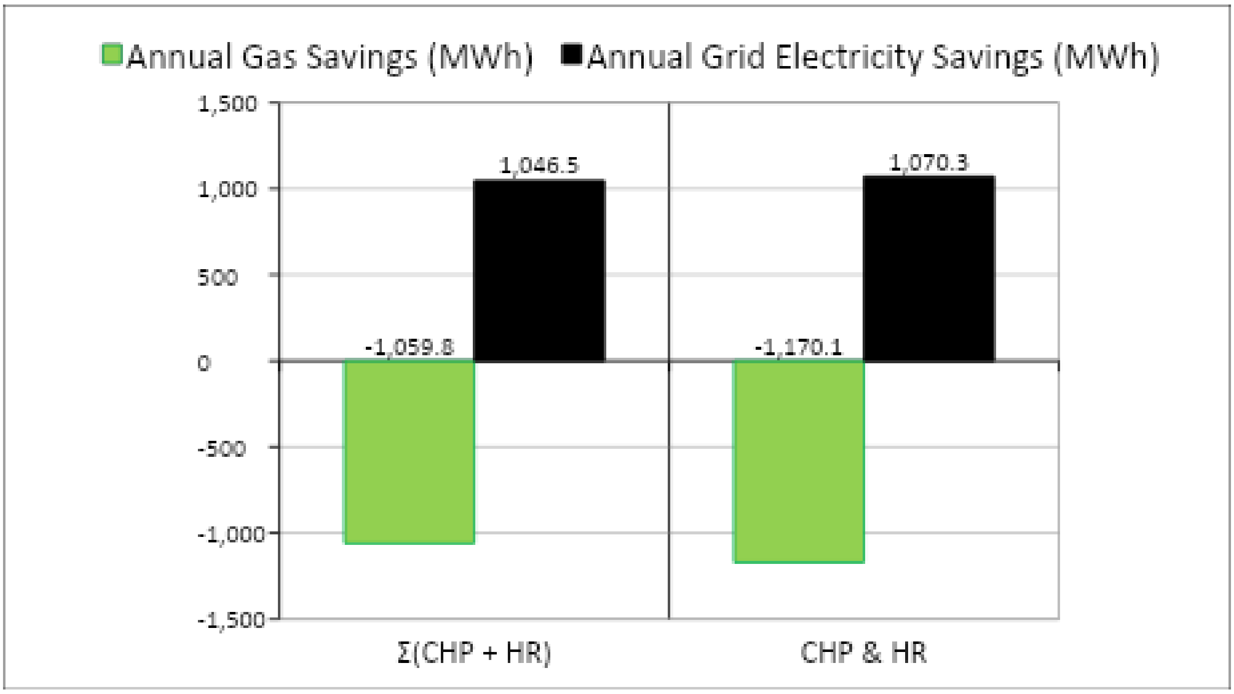


Figure 12-7: Annual gas & grid electricity savings from individual and combined CHP and HR plant

12.3.3 IB & HR

The ice bank and heat recovery chiller have an effect on each other when used together. The energy cost savings are enhanced and the CO_2 savings are diminished when the systems are combined as shown in Figure 12-8. The systems consume more gas and consume less grid electricity when combined as shown in Figure 12-9.

During winter, the ice bank is capable of providing the entire cooling load over the day. The chiller therefore only operates at night time in winter when the ice bank is being charged. The COP of the chiller is influenced in a similar way to the individual cases. The combined effect of the greater PLR and lower ambient temperatures at night and the higher temperature lift required result in a lower chiller electrical consumption over the year.

The gas consumption savings are reduced due to the lower number of operating hours of the heat recovery chiller and the savings in grid electrical consumption are increased due to the more efficient operation of the chiller as shown in Figure 12-9. This increase in gas consumption and decrease in grid electricity consumption has the combined effect of enhancing the energy cost savings and diminishing the CO_2 emission savings achieved by combining the systems.

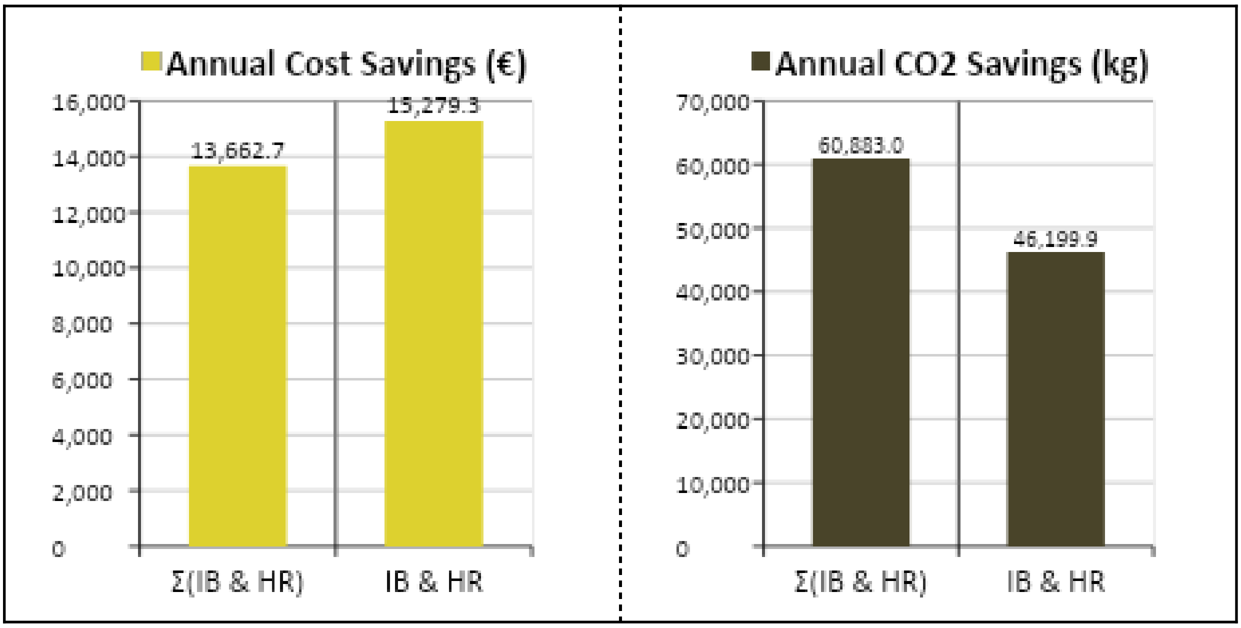


Figure 12-8: Annual energy cost & CO_2 emission savings from individual and combined IB and HR plant

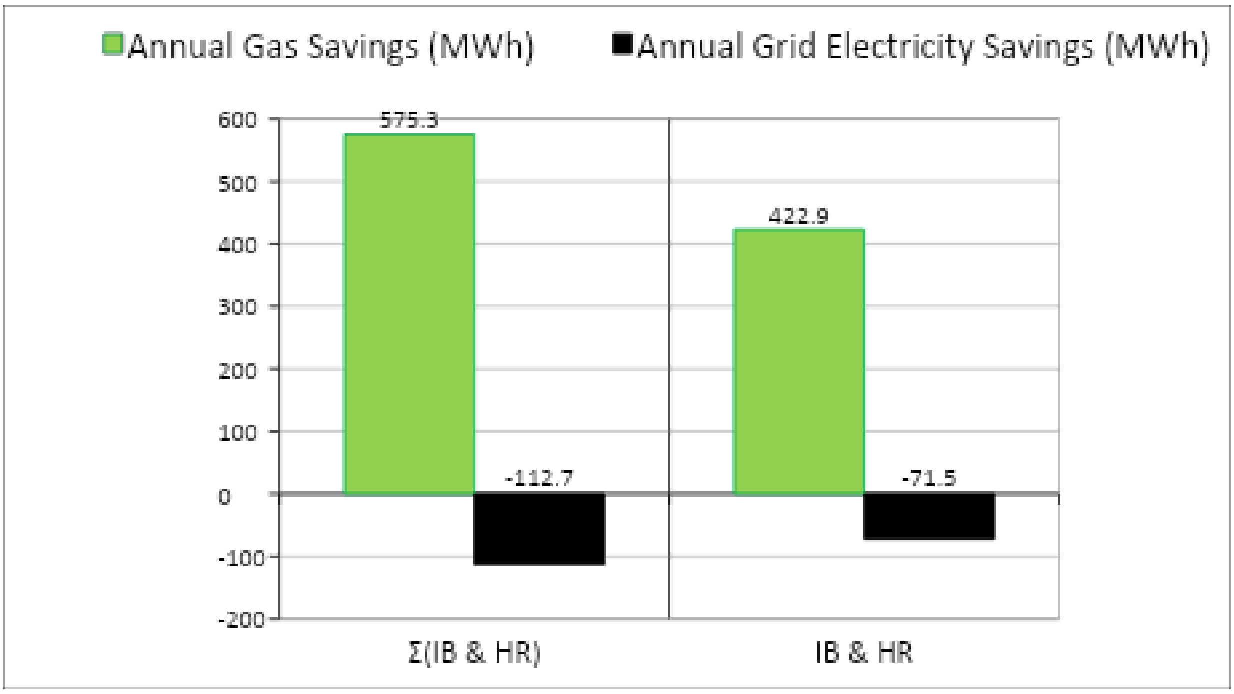


Figure 12-9: Annual gas & grid electricity savings from individual and combined IB and HR plant

12.4 Complete Use of Plant

The combined use of the CHP unit, ice bank and heat recovery chiller results in energy cost and CO_2 emission savings of approximately €113,000 and 226,600kg respectively. Figure 12-10 and Figure 12-11 show the annual energy cost, CO_2 emission and gas and grid electricity energy use for the basic case and for the case when all the plant items are used together.

Each of the compatibility issues mentioned for the combined use of plant in the previous sections are in effect when all of the plant items are used together.

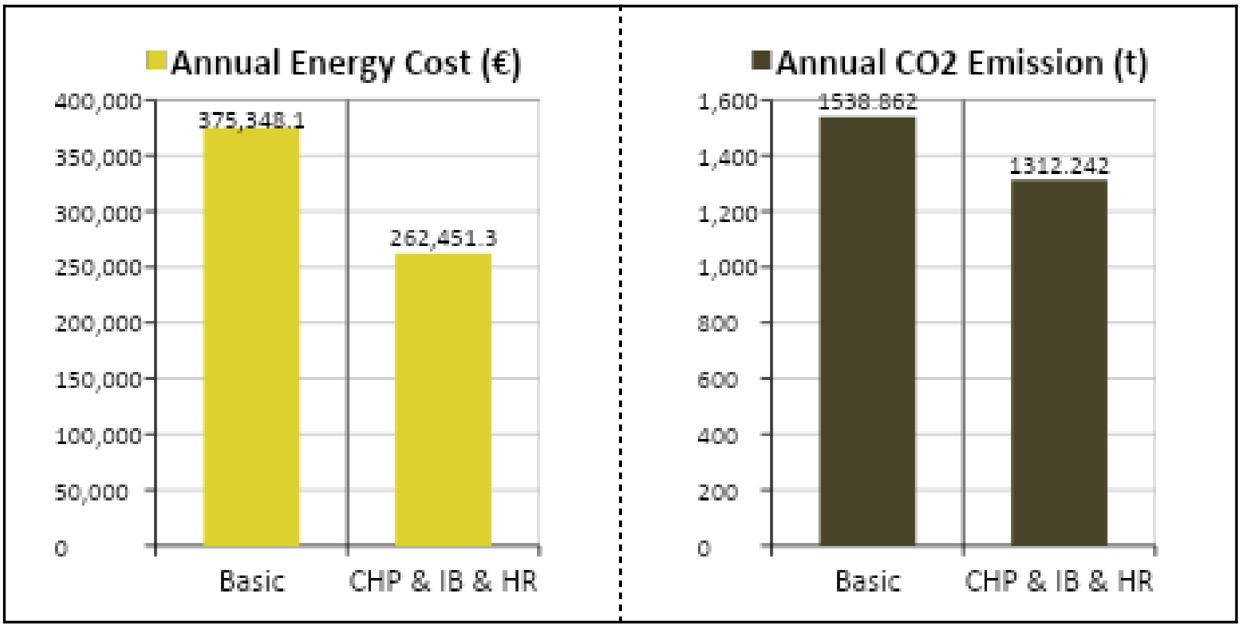


Figure 12-10: Annual energy cost & CO_2 emission from basic case and combined use of CHP, IB and HR plant

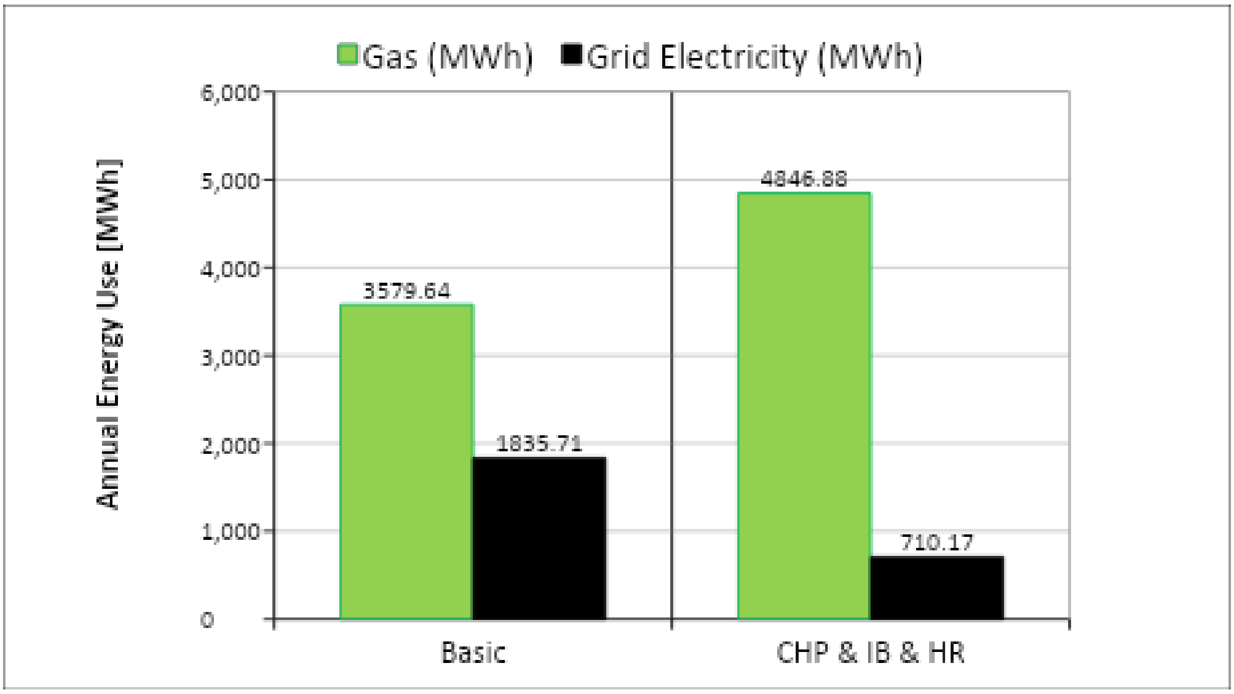


Figure 12-11: Annual gas & grid electricity use from basic case and combined use of CHP, IB and HR plant

12.5 Compatibility Issues Identified

The low energy plant compatibility issues identified in this chapter were as follows:

- The CHP unit *steals* some of the heat recovery chiller's heating load, forcing it to operate in cooling only or cooling main mode more often.
- The increased chiller electrical load caused by the charging of the ice bank has no effect on the CHP as it already operates at full power output.
- The ice bank shifts some of the NGI building's cooling load from daytime to night time. The number of hours the heat recovery chiller operates is reduced due to the ice bank providing all of the cooling during the day in winter.
- The COP of the chiller is effected by the following:
    - Larger PLRs due to the additional charging load at night
    - Lower ambient air temperatures while operating at night
    - Higher temperature lifts required when charging the ice bank or operating in heat recovery mode.

- Altered frequencies of operating modes due to the ice bank and CHP unit

These compatibility issues affect the annual energy cost and CO_2 emission savings achieved by the low energy plant items. Some of the issues have a positive effect while others have a negative effect. The compatibility issues raised in this chapter are not significant enough to remove any of the low energy plant items from the NGI system design.

Table 12-1 summarises the annual total energy cost, total CO_2 emission, total gas consumption and total grid electricity consumption for the NGI building for each combination of low energy plant items. The combination which achieves the highest reduction of each variable is highlighted in green and the combination which achieves the highest increase is highlighted in red.

It can be seen from Table 12-1 that the lowest annual energy cost is achieved when each of the plant items are used. There is a slight reduction in annual CO_2 emissions when the ice bank is not used. However, the energy cost savings of approximately €10,500 from including the ice bank outweigh the resulting additional 2 tonnes of CO_2 emissions.

Table 12-1: Summary table of simulations for each plant combination

Simulation	Annual Energy Cost (€)	Annual CO2 Emission (t)	Annual Gas Consumption (MWh)	Annual Grid Electricity Consumption (MWh)
Basic	375,348	1,539	3,580	1,836
CHP	277,376	1,354	5,215	654
IB	366,851	1,534	3,580	1,813
HR	370,182	1,483	3,004	1,971
CHP & IB	268,880	1,350	5,215	631
CHP & HR	272,929	1,310	4,750	765
IB & HR	360,069	1,493	3,157	1,907
CHP & IB & HR	262,451	1,312	4,847	710

12.6 Justification of Low Energy Plant Alternatives

The capital cost of each of the low energy plant alternatives included in BDP's design will ultimately be provided by the tax payer. Therefore the inclusion of each of the technologies must be justified. The capital cost of each of the low energy plant alternatives and their additional pipes, controls etc. were provided by BDP and are shown in Table 12-2.

Table 12-2: Capital cost of low energy plant alternatives (BDP)

Plant Item	Cost of Plant Item	Cost of Pipes/Controls/etc.	Total Capital Cost
CHP Unit	€150,000	€10,000	€160,000
Ice Banks	€20,000	€8,000	€28,000
Heat Recovery Chiller	€10,000	€8,000	€18,000

A simple payback period and a net present value (NPV) after 10 years were calculated for each combination of plant using equations (12-1) and (12-2) respectively. The NPV was calculated over 10 years as it is expected that the CHP unit will be approaching the end of its operating life at this time. A discount rate of 10% was used for the NPV calculation.

$$Simple\ Payback = \frac{Total\ Capital\ Cost}{Annual\ Savings}\ [\#\ years] \tag{12-1}$$

$$NPV = \sum_{i=1}^{10} \frac{Annual\ Savings}{(1+0.10)^{i}} - Total\ Capital\ Cost\ [€] \tag{12-2}$$

The *Annual Savings* used in these equations were determined from the *Annual Energy Cost* values in Table 12-1. They also included an additional annual CHP unit maintenance cost of €6,000. The simple payback period and NPV after 10 years of each plant combination are summarised in Table 12-3.

Table 12-3: Financial summary of low energy plant alternative combinations

Plant Combination	Annual Maintenance Costs	Annual Savings	Simple Payback Period (# years)	NPV (10 years)
CHP	€6,000	€91,972	1.74	€405,126
IB	€0	€8,497	3.30	€24,208
HR	€0	€5,166	3.48	€13,743
CHP & IB	€6,000	€100,468	1.87	€429,335
CHP & HR	€6,000	€96,419	1.85	€414,451
IB & HR	€0	€15,279	3.01	€47,885
CHP & IB & HR	€6,000	€106,897	1.93	€450,835

The plant combination which achieves the lowest simple payback period is the CHP unit on its own. However, it is worth noting that the CHP unit manufacturer insists that the unit is run at no more than 70% of its maximum output. This extends the simple payback period of the plant combinations which include the CHP unit, but not significantly.

The ice banks and heat recovery chiller have much lower capital costs than the CHP unit but longer payback periods. The payback periods of the ice banks and heat recovery chiller are greatly reduced when combined with the CHP unit. The relatively larger savings achieved by the CHP unit help to quickly pay for the relatively small capital costs of the ice banks and heat recovery chiller without significantly affecting the payback period of the CHP unit.

The NPV is an indicator of how much value an investment adds to a project and is perhaps a more appropriate justification method than using a simple payback period. The greatest NPV is achieved when the CHP unit, the ice banks and the heat recovery chiller are all used. This indicates that the tax payer will achieve the greatest value for money when each of the low energy plant alternatives are included in the design.

There are more considerations than just the monetary value of the project which help to justify the use of each of the low energy plant alternatives. By using a mix of systems, the gas and grid electrical consumption of the NGI building can be manipulated according to their respective costs and CO_2 intensities present at the time. It is expected that the CO_2 intensity of grid electricity will decrease within the lifetime of the project as more renewables are added to the national grid. After a number of years, by which time the CHP unit will have paid for itself, the CHP unit may be de-prioritised in favour of the ASHP. The NGI is a public building and may be given a carbon target to achieve at some stage within the lifetime of the plant items. In this case, the ASHP would certainly be prioritised over the CHP unit or boilers.

The Beit wing AHUs are to be refurbished in a number of years and will include a number of low temperature heating coils. This will increase the available lower temperature heating load and enhance the savings achieved by the heat recovery chiller. The CHP unit will also be decommissioned after approximately 10 years whereas the ASHP will operate for approximately 20 years.

The inclusion of the ice bank is also beneficial to the tax payer. It will contribute to the smoothing of the electrical demand on the grid which is a goal of national interest.

13 Conclusion

This thesis evaluated and optimised the low energy plant alternatives to be used in the refurbishment of the National Gallery of Ireland. The mechanical and electrical system design provided by BDP was modelled using a combination of TRNSYS and IES VE. The optimisation of the NGI CHP unit, ice banks and heat recovery chiller and the evaluation of the NGI low energy plant alternatives are concluded in the following subsections.

13.1 Optimisation of the NGI CHP Unit

Energy cost and CO_2 emission savings from a CHP unit depend on the performance of the CHP unit over its range of power outputs, whether the heat output of the CHP unit can be utilised and the difference in cost and CO_2 intensity between the electricity displaced by the CHP unit and the fuel used by the CHP unit. The benefits of the CHP unit are increased when the CHP unit operates at full power output as the maximum electrical efficiency is achieved. A higher electrical efficiency means that more electricity and less heat are produced per unit of fuel used.

CHP units produce more heat at higher power outputs and there may not be sufficient heating loads available to utilise the CHP unit's heat output. In this case, it may be more economical or less CO_2 intensive to reduce the power output of the CHP unit so that all of its heat is utilised and accept the reduced electrical efficiency of the unit. The deciding factor for modulating the CHP unit in this fashion is the difference in the cost and CO_2 intensity between the electricity displaced by the CHP unit and the fuel used by the CHP unit. The energy cost and CO_2 benefits of using a CHP unit are enhanced when the cost and CO_2 intensity of the electricity which the CHP unit displaces are much greater than the cost and CO_2 intensity of the fuel used by the CHP unit.

It was found that the optimum CHP unit control philosophy to minimise energy costs for the NGI building was to operate the CHP unit at full output during on-peak electrical tariffs and modulate the CHP unit according to the heating load available during off-peak electrical tariffs. If CO_2 emissions are to be minimised, the CHP unit should be modulated according to the heating load available at all times. The CHP unit's heat output should also be given priority use ahead of the NGI chiller's heat at all times to minimise both energy costs and CO_2 emissions.

13.2 Optimisation of the NGI Ice Banks

A number of charging and discharging options were analysed for the NGI ice banks. The charging options analysed were prolonged charge, chiller load dependent charge and ambient air temperature dependent charge. The discharging options analysed were store priority discharge, chiller priority discharge, constant proportion discharge and level off discharge. The optimum ice bank control philosophy for the NGI building was determined to be a combination of prolonged charge and chiller priority discharge options.

Each charge option analysed provided the same total amount of charging but their charge rates and charging times varied. The prolonged charge option was found to be the optimum charge option. It resulted in the greatest annual energy cost and CO_2 savings due to a more constant chiller COP over the entire charging period. The chiller load dependent charge option and ambient air temperature dependent charge option resulted in the ice bank charging very quickly. The COP of the chiller was improved greatly while the ice bank was charging but suffered for the remainder of the charging period. The ambient air temperature dependent charge option resulted in slightly lower annual energy costs and CO_2 emissions than the chiller dependent load condition as it charged the ice bank during the coldest hours of the charging period, which improved the COP of the chiller further.

Unlike the charging options analysed, the discharge options analysed did not all provide the same amount of cooling. The cooling provided by each discharge option depended on the control logic used and the discharge option's ability to accurately predict the cooling load to be met by the ice bank over the course of the discharge period. It was found that the constant proportion discharge option of 100% achieved the greatest annual energy savings and CO_2 emissions, followed closely by the chiller priority discharge option. The savings achieved by each discharge option depended on the resulting chiller performance and the quantity of cooling provided by the ice bank. The constant proportion discharge option of 100% resulted in the greatest savings simply because it ensured that the entire ice bank charge was utilised each discharge period. The optimum discharge option was determined to be the chiller priority discharge option as it achieved savings very close to that of the constant proportion discharge and provided the added benefit of reducing the peak NGI electrical demand on the grid. It is likely that this would reduce the financial penalties from exceeding the maximum import capacity of the NGI building although the potential savings were not quantified. If a chiller priority discharge option is to be employed by the NGI ice bank, it should be capable of accurately predicting the cooling loads over the discharge period so that the maximum savings can be achieved.

13.3 Optimisation of the NGI ASHP

The NGI chiller was capable of operating as an air source heat pump for a significant proportion of the year. The potential for the operation of the ASHP depended on the NGI heating and cooling loads. It was found that the ASHP's heating only mode could be used for a significant duration of the year. This operating mode could be used during daytime in the heating season when the ice bank provides all of the NGI's cooling loads. The ASHP's heating main mode could only be used for limited durations of the year as the heating load was rarely larger than the combined cooling and ice bank charging loads.

Two methods were used to indicate when the NGI's chiller should operate as an air source heat pump. The first method was to calculate the minimum COPs that had to be achieved for the ASHP to be favourable over the boiler plant and to compare them against the actual COPs achieved by the chiller when operating as an ASHP. The second method was to determine the relative heating prices for both the ASHP and boiler plant. Both methods found that the ASHP should only be enabled during off-peak electrical tariffs if energy costs are to be minimised. If CO_2 emissions are to be minimised, the ASHP should be enabled at all times. These findings are only applicable to the gas and grid electrical tariffs and CO_2 intensities used in the analysis. The ASHP becomes more favourable over the boiler plant when the difference between the cost and CO_2 intensity of the fuel used by the boiler and the electricity used by the ASHP decreases.

13.4 Evaluation of the NGI Low Energy Plant Alternatives

A number of compatibility issues were identified between the NGI low energy plant alternatives. The CHP unit and the heat recovery chiller were found to compete for the same heating loads, particularly during the summer months. The ice bank charging and discharging options influenced the performance and operating modes of the chiller. The ice bank altered the chiller's electrical consumption. This had no effect on the CHP unit as the NGI electrical load exceeded the maximum output of the CHP unit at all times. If a CHP unit with a greater maximum power output had been used, the ice bank would have had an effect on the CHP unit. The annual energy cost and CO_2 emission savings achieved by the combined use of the low energy plant items was not equal to the sum of the savings achieved by the individual use of the low energy plant items due to the compatibility issues mentioned above. However, significant savings to both annual energy costs and CO_2 emissions are achieved from the use of the low energy plant items.

13.5 Final Conclusion

The overall aim of this thesis project was to evaluate and optimise a number of low energy plant items that have been included in BDP's mechanical and electrical system design for the refurbishment of the National Gallery of Ireland. Significant savings to both energy cost and CO_2 emissions were achieved from using BDP's mechanical and electrical system design over conventional designs. Each of the low energy plant items used contributed towards these savings. The net present value of each combination of plant after 10 years was calculated. The plant combination which achieved the greatest NPV was the combined use of the CHP unit, the heat recovery chiller and the ice banks. To achieve the greatest savings from the design, the optimum control philosophies identified for each plant item should be used. In addition to the financial benefits of including the plant items, the ASHP provides a less CO_2 intensive heating option for the NGI. The ice bank also contributes to the smoothing of the electrical demand on the national grid. Therefore each plant item's inclusion in BDP's design for the NGI refurbishment can be justified.

13.6 Future Work

The analysis carried out on the NGI low energy plant alternatives was not exhaustive. A number of analyses could still be carried such as analysing the performance, energy cost savings and CO_2 savings achieved by a larger or smaller CHP unit or a greater or less number of ice banks. Another analysis possibility would be to investigate the advantages and disadvantages of connecting the chiller and ice bank in series or parallel.

The TRNSYS model developed has much potential for improvement. Additional features could be included such as a consideration for the maximum import capacity of the NGI building or an ability to switch between plant models. The user interface of the model could also be improved and the components within the simulation studio could be condensed and tidied. Ultimately, the TRNSYS model could be generalised so that any combination and configuration of the low energy plant items could be analysed for any set of load data.

References

Arnold, D. et al., 1994. *CIBSE TM18: Ice Storage.* 1st ed. London: The Chartered Institution of Building Services Engineers.

ASHRAE, 2008. *ASHRAE Handbook - HVAC Systems and Equipment.* SI ed. Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

Butler, D., 2005. Ice Storage systems. In: V. Crisp, ed. *CIBSE Guide B - Heating, ventilating, air conditioning and refrigeration.* London: The Chartered Institution of Building Services Engineers, pp. 4-37.

Byrne, P., Miriel, J. & Lenat, Y., 2011. Experimental study of an air-source heat pump for simultaneous heating and cooling - Part 2: Dynamic behaviour and two phase thermosiphon defrosting technique. *Applied Energy,* 88(9), pp. 3072-2078.

Calmac, 2014. *Icebank Energy Storage Model C Tank.* [Online] Available at: http://www.calmac.com/icebank-energy-storage-model-c [Accessed 03 09 2014].

Chaichana, C., Charters, W. W. & Aye, L., 2001. An ice thermal storage computer model. *Applied Thermal Engineering,* 21(17), pp. 1769-1778.

Cheshire, D., 2012. *CIBSE Guide F - Energy efficiency in buildings.* 3rd ed. London: The Chartered Institution of Building Services Engineers.

CIBSE, 2013. Application of small-scale combined heat and power. *CIBSE Journal,* 5(6), pp. 59-61.

Crawley, D., Hand, J., Kummert, M. & Griffith, B., 2005. *Contrasting The Capabilities of Building Energy Performance Simulation Programs,* Washington DC: US Department of Energy.

DesignBuilder Software Ltd., 2014. *Building Performance Analysis Software.* [Online] Available at: http://www.designbuilder.co.uk/documents/flyers/BuildingPerfomanceAnalysisSoftware.pdf [Accessed 23 07 2014].

Dincer, I., 2002. On thermal energy storage systems and applications in buildings. *Energy and Buildings,* 34(4), pp. 337-388.

Dwyer, T., 2011. Power driver. *CIBSE Journal,* 3(2), pp. 38-44.

Eirgrid, 2014. *CO2 Intensity.* [Online] Available at: http://www.eirgrid.com/operations/systemperformancedata/co2intensity/ [Accessed 1 9 2014].

EnergyPlus, 2013. *Getting Started with EnergyPlus,* Berkeley: US Department of Energy.

Erek, A. & Dincer, I., 2009. Numerical heat transfer analysis of encapsulated ice thermal energy storage system with variable heat transfer coefficient in downstream. *International Journal of Heat and Mass Transfer,* 52(3-4), pp. 851-859.

Habeeullah, B., 2007. Economic feasibility of thermal energy storage systems. *Energy and Buildings,* 39(3), pp. 355-363.

Hasnain, S., 1998. Review on sustainable thermal energy storage technologies, Part 2: cool thermal storage. *Energy Conversion and Management,* 39(11), pp. 1139-1153.

Henze, G. P., Krarti, M. & Brandemuehl, M. J., 2003. Guidelines for improved performance of ice storage systems. *Energy and Buildings,* 35(2), pp. 111-127.
IES, 2014. *Manuals.* [Online] Available at: http://www.iesve.com/support/userguides [Accessed 23 07 2014].
IES, 2014. *Special Student Software Offer.* [Online] Available at: http://www.iesve.com/software/download/ve-for-students [Accessed 23 07 2014].
Jones, P. & Day, T., 2009. *KS14 Energy efficient heating: an overview,* London: The Chartered Institution of Building Services Engineers.
Joo, Y. et al., 2011. Performance characteristics of a simultaneos cooling and heating multi-heat pump at partial load conditions. *International Journal of Refrigeration,* 34(4), pp. 893-901.
Kang, H. et al., 2009. Experimental study on the performance of a simultaneous heating and cooling multi-heat pump with the variation of operation mode. *International Journal of Refrigeration,* 32(6), pp. 1452-1459.
Lee, A. H. & Jones, J. W., 1996. Modeling of an ice-on-coil thermal energy storage system. *Energy Conversion and Management,* 37(10), pp. 1493-1407.
NGI, 2014. *About the Collection.* [Online] Available at: http://www.nationalgallery.ie/Collection/About_the_Collection.aspx [Accessed 19 07 2014].
NGI, 2014. *History of the Institution.* [Online] Available at: http://www.nationalgallery.ie/aboutus/History.aspx [Accessed 19 07 2014].
NGI, 2014. *The evolution of the Gallery building.* [Online] Available at: http://www.nationalgallery.ie/aboutus/Gallery_150/The_Past/History/The_building.aspx [Accessed 19 07 2014].
NGI, 2014. *The Future of the Gallery.* [Online] Available at: http://www.nationalgallery.ie/aboutus/Gallery_150/The_Future.aspx [Accessed 19 07 2014].
Rishel, J. & Kincald, B., 2007. Reducing Energy Costs with Condensing Boilers & Heat Recovery Chillers. *ASHRAE Journal,* 49(3), pp. 46-55.
Sanaye, S. & Shirazi, A., 2013. Thermo-economic optimization of an ice thermal energy storage system for air-conditioning applications. *Energy and Buildings,* 60(May), pp. 100-109.
Soltan, B. K. & Ardehali, M. M., 2003. Numerical simulation of water solidification phenomenon for ice-on-coil thermal energy storage application. *Energy Conversion and Management,* 44(1), pp. 85-92.
The Carbon Trust, 2010. *Introducing CHP.* [Online] Available at: http://www.carbontrust.com/media/19529/ctv044_introducing_combined_heat_and_power.pdf [Accessed 16 07 2014].
The Carbon Trust, 2011. *Heat Recovery,* London: The Carbon Trust.

Warburton, P. et al., 2009. *CIBSE Guide H - Building control systems.* 2nd ed. London: The Chartered Institution of Building Services Engineers.

Woods, P., 2013. *CIBSE AM12: Combined Heat and Power for Buildings.* 3rd ed. London: The Chartered Institution of Building Services Engineers.

Yau, Y. & Rismanchi, B., 2012. A review on cool thermal storage technologies and operating strategies. *Renewable and Sustainable Energy Reviews,* 16(1), pp. 787-797.

Zhu, Y. & Zhang, Y., 2001. Modeling of thermal processes for internal melt ice-on-coil tank including ice-water density difference. *Energy and Buildings,* 33(4), pp. 363-370.

Zogg, R., Roth, K. & Brodrick, J., 2005. Using CHP Systems In Commercial Buildings. *ASHRAE Journal,* 47(9).

Appendices

The thesis appendix is provided on a DVD attached to the back cover of this thesis. The thesis appendix is divided into six appendices: *A, B, C, D, E* and *F*. The contents of these appendices are summarised below. Each of the appendices contains a "*ReadMe*" text file which further explains the data contained in each appendix.

Appendix A – BDP Documents

This appendix contains the documents provided by BDP for this thesis. Some of the documents provided by BDP are confidential and could not be included in the appendix.

Sub division	Contents
A1	BDP's mechanical system schematics
A2	Average grid CO_2 intensities calculated by BDP

Appendix B – Plant Performance Data

This appendix contains the data sourced for each of the low energy plant alternatives included in BDP's mechanical and electrical design for the refurbishment of the NGI.

Sub division	Contents
B1	CHP unit data
B2	Heat recovery chiller data
B3	Ice bank data

Appendix C – TRNSYS Model Data

This appendix contains data required for the TRNSYS model created by the author.

Sub division	Contents
C1	Component proforma files
C2	Dynamic link libraries (DLLs)
C3	Simulation studio files

Appendix D – Modelled Plant Performance

This appendix contains the Excel workbooks used to develop and test the equations used to model the low energy plant alternatives.

<u>Sub division</u> <u>Contents</u>

D1	CHP unit model development workbook
D2	Heat recovery chiller model development workbook
D3	Ice bank model development workbook

Appendix E – Excel Workbooks & Simulation Results

This appendix contains the Excel workbooks that were used in conjunction with the TRNSYS model developed by the author. It also contains the TRNSYS model outputs or simulation results for each of the simulations run in this thesis.

Sub division	Contents
E1	Excel workbooks used in conjunction with TRNSYS model
E2	Simulation results

Appendix F – Original Code

This appendix contains copies of all of the original code written for this thesis.