

Shallow Geothermal Systems: Individual and District Applications

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Abstract

Worldwide energy use is expected to rise due to an increase in population and global warming. About half of this energy use is for space heating and cooling for buildings, where electricity (mostly derived from fossil fuels) and natural gas are the most common sources of energy. To achieve long term energy sustainability, electricity and natural gas consumption needs to be reduced.

One way to achieve this reduction is by utilising shallow geothermal system or ground source heat pump (GSHP) system technology. This technology utilises the ground as a heat source or a heat sink to provide sustainable heating and cooling for buildings. The use of this technology has been growing worldwide. However, information and high-quality datasets of GSHP systems are still rare in Australia, leading to installations with low efficiency and high installation costs. This research aims to contribute to the understanding of GSHP systems under Australian climatic, cost and emission conditions, including how to improve their viability and uptake.

The first part of this research aims to address this lack of availability of quality datasets. To do this, a full-scale monitoring project was undertaken. This thesis presents the performance data from 10 monitored residential and small commercial GSHP system installations in the greater Melbourne area. The measured data reveals that a GSHP system can perform well under Melbourne climatic condition, with an estimated coefficient of performance between 2 and 4.9.

One common trend in all of the monitored properties is that they are used only around 10 to 20% of the year, which is much smaller compared to the expected usage based on typical design methods. For this reason, a more detailed comparison was conducted for two properties with the lowest and highest system usage. The comparison indicates that the differences in the usage patterns imposed by the occupiers can significantly impact the potential cost-effectiveness and environmental benefits of the GSHP system. This suggests that in general, a GSHP system can be an alternative heating and cooling options under Melbourne climatic and geological conditions, but they have to be designed, installed and used appropriately. Otherwise, this may lead to an inefficient system with a long payback period.

One potential explanation behind the moderate GSHP system usage described above is the temperate climatic conditions of Melbourne, which requires only moderate heating and cooling. For these conditions, a hybrid combination between GSHP and conventional systems may be preferred to maximise the benefits from both systems. A hybrid GSHP (HGSHP) system means a GSHP system that is sized to provide the baseload thermal energy for a building and this system is supported by a conventional system during the hottest and coldest days of the year.

This leads to the next part of this research where an HGSHP system design method is proposed with the objective that considers both costs and emissions by using a Pareto optimum approach. This analytical study is extended to cover different climatic, cost and emission conditions across several Australian cities. The results reveal that HGSHP systems can have a lower lifetime cost than GSHP or conventional systems. However, this hybrid system mix with the lowest lifetime cost is not necessarily the same as the one with the lowest lifetime emission. Overall, this research may provide a basis on which decisions about whether to install an HGSHP system with the objective to minimise their lifetime costs or emissions. A solution which considers both factors with equal weight is also provided herein.

The last part of this research considers the possibility to combining several individual HGSHS systems into a district arrangement. This is called a district HGSHS system and this is possible because buildings are located close to each other in the urban area. The results indicate that district HGSHS systems can reduce capital and operational costs compared to individual HGSHS systems. The highest financial savings occur when buildings with significantly contrasting thermal load patterns are combined together, for example, combining heating dominant with cooling dominant buildings. Combining more buildings lead to higher financial savings, but this follows the law of diminishing returns.

Altogether, the findings from each chapter are expected to contribute incrementally to improving our knowledge of GSHP system technology as well as providing more real-life performance data. The insights from this research may also be applicable to other locations with similar climatic, cost and emission conditions. Further, based on the outcomes of the work covered in this thesis, stakeholders may be able to make more informed decisions on design, installation and operation of GSHP systems. These should also allow the development of more appropriate public policy to encourage the growth of the shallow geothermal industry.

Declaration

This is to certify that:

- the thesis comprises only my original work towards the degree of Doctor of Philosophy;
- due acknowledgement has been made in text to all other materials used,
- the thesis is fewer than 80,000 words in length, exclusive of tables, maps, bibliographies and appendices

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Publications relating to this work

As part of the research undertaken to produce this doctoral thesis, several independent research works were produced and are described here as they related directly to the chapters of this thesis. Four of the chapters have been either published, submitted for review or about to be submitted:

1. Aditya GR, Narsilio GA, Johnston IW. Usage behaviour comparison based on field measurements of ground source heat pump systems in Melbourne, Australia. Expected to be submitted to *Energy*.
2. Aditya GR, Mikhaylova O, Narsilio GA, Johnston IW. Comparative costs of ground source heat pump systems against other forms of heating and cooling for different climatic conditions. Submitted to *Building and Environment*.
3. Aditya GR, Narsilio GA. Environmental assessment of hybrid ground source heat pump systems. *Geothermics*. **87**: 101868
4. Aditya GR, Narsilio GA. District ground source heat pump systems for temperate climatic conditions. Submitted to *Applied Thermal Engineering*.

The above publications are the basis of Chapters 4, 5, 6 and 7 of this thesis and are inserted in the body of the text as the original submitted work. However, the text, figures and tables have been modified to be consistent with the formatting of this thesis.

Additionally, two published conference papers that contain preliminary results have been included in Appendix A, together with the published *Geothermics* journal paper.

- 1 Aditya G, Narsilio G, Johnston I, Disfani M. Full-Scale Instrumented Residential Ground Source Heat Pump Systems in Melbourne, Australia. International Symposium on Energy Geotechnics, Lausanne, Switzerland. Springer, 2018, p. 185-91.
- 2 Aditya G, Mikhaylova O, Narsilio GA, Johnston IW. Financial assessment of ground source heat pump systems against other selected heating and cooling systems for Australian conditions. IGSHPA research track Stockholm, Sweden, 2019, p. 170-8.
- 3 Aditya, G, Narsilio, G. A., (2020). Environmental assessment of hybrid ground source heat pump systems. *Geothermics* **87**: 101868.

In each case, I contributed more than 50% of the work, including the installation of instrumentation equipment, data collection, data analysis, creation of figures and tables presenting research findings, and first drafts of all written words. The co-authors in each case contributed with their ideas and valuable insights, as well as with reviewing the written material, editing and providing comments, feedback and advice towards the improvement and clarity of manuscripts, figures and contents. The required co-author authorisation forms have been provided with this submission for all the publications and future publications listed above.

Furthermore, I have been involved as a co-author in other publications during this PhD study. They have presented me the opportunity to develop expertise on GSHP systems but they are not part of the thesis since I am not the primary author. My contributions include sensors installation and data collection and analysis as part of the GSHP system monitoring project described in Chapters 3 and 4. Those publications that I was involved as a co-author are:

1. Lu Q, Narsilio GA, Aditya GR, Johnston IW. Economic analysis of vertical ground source heat pump systems in Melbourne. *Energy*. 2017;125:107-17.
2. Lu Q, Narsilio GA, Aditya GR, Johnston IW. Cost and performance data for residential buildings fitted with GSHP systems in Melbourne Australia. *Data in Brief*. 2017.
3. Jensen-Page L, Narsilio GA, Johnston IW, Aditya GR, Mikhaylova, O. Uncertainty in Ground Thermal Conductivity: Factor of Safety Based Geothermal Design. Submitted to *Geotechnique*.
4. Weeratunge H, Aditya GR, de Hoog J, Dunstall S, Narsilio GA, Halgamuge S. Performance analysis and comparison of hybrid ground source heat pump systems in fourteen cities. About to be submitted for publication

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Thank you to my girlfriend, Iris Setiaji who has always encouraged me, cheer me up when I am down, listen to my endless complaint and eternally being patient. Without you, I probably would never complete this PhD.

Last but not least, I thank family and friends for their support, unconditional love and care throughout this journey. Some of you have listened to my endless complaints about research and work. Whether its sports, games or foods, you have helped me to enjoy my life for the last few years and keep my stress level low. I could not ask for more.

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1 Introduction

1.1 Background

Worldwide energy use is expected to rise due to an increase in population and global warming. About half of this energy use is for space heating and cooling for buildings, where electricity (mostly derived from fossil fuels) and natural gas are the most common sources of energy. To achieve long term energy sustainability, electricity and natural gas consumption needs to be reduced.

One way to achieve this reduction is by utilising shallow geothermal system or ground source heat pump (GSHP) system technology. The number of installations of this technology has been growing worldwide along with various innovations developed to make the technology even more efficient, sustainable and economically viable.

Even though there have been experimental studies of GSHP systems published worldwide, the availability of high-quality datasets on performance and usage patterns are still rare, especially under real-life thermal loads. In Australia, the availability of these datasets is further limited due to the small number of GSHP systems installed, and fewer still that have their performance monitored in detail. Therefore, GSHP system technology is not widely known in Australia. Further, even amongst those who are aware of the technology, they are sceptical about the performance and cost of the technology under Australian climatic and pricing conditions.

To redress this, The University of Melbourne has been undertaking a full-scale pilot direct geothermal energy demonstration project, whereby the performance data from a number of properties in greater Melbourne have been collected for several years. This pilot demonstration project is the focus of the first half of this thesis. The results and learnings from this monitoring project are expected to contribute to future GSHP system installation in Australia, especially in the greater Melbourne area.

The above monitoring program has focused on collecting cost and performance data from individual installations. However, economies of scale can be achieved by combining GSHP and traditional heating, ventilating and air conditioning (HVAC) systems, forming hybrid GSHP systems. Even greater economies of scale and further optimisations can be achieved by combining several individual GSHP systems into a district system. This is possible in an urban environment, where the ground loops of a GSHP system can be connected to multiple buildings through a common water loop. This configuration is called a district GSHP system (DGSHP system). In such configuration, the base load thermal energy to a building is provided by a district GSHP system and if needed, additional conventional systems can be installed to support the DGSHP systems during the hottest and coldest days of the year. With this configuration, different buildings can even indirectly help to heat and cool each other without the need to use the ground heat exchangers. In an extreme scenario, if one building requires cooling and another requires heating, the first building can reject the associated heat via their own heat pumps into a common water loop and this heat can be extracted by the heat pumps of the second building and be used for heating. Compared to individual GSHP systems, DGSHP systems typically require fewer ground loops installed (to exchange heat with the ground) and have lower overall external energy consumption. These will lead to lower capital and operational costs of the systems. The second half of this thesis explores the financial and environmental feasibility of utilising DGSHP systems under Australian climatic conditions.

1.2 Research Objectives

This work aims to contribute to the understanding of GSHP systems in both individual and district applications for Australian climatic, costs and emissions conditions. To achieve this aim, the following objectives have been identified:

- To evaluate the performance of residential GSHP systems under actual operating conditions and geologies typically encountered in Melbourne, Australia
- To investigate the potential impact of user-behaviour on the performance of GSHP systems in Melbourne
- To conduct a financial and an environmental assessment of hybrid GSHP systems under Australian climatic, costs and emissions conditions
- To investigate the use and optimisation of DGSHP systems under various thermal load patterns and building combinations

1.3 Thesis Outline

This thesis comprises 8 chapters and 4 appendices. Some of the chapters are in the process of being published (see section *Publications relating to this work*). The relevant literature reviews are also included in each chapter.

Chapter 1 (this chapter) provides background, the motivation and outline of this thesis.

Chapter 2 presents a literature review. Background information on GSHP systems focusing on experimental work around the world is presented. A section on hybrid and district GSHP system configurations is presented to review recent advances in this field.

Chapter 3 describes the experimental set up for residential GSHP systems monitoring project in Melbourne, Australia. In this chapter, the location, geologies, ground heat exchangers (GHEs), GSHPs, the heating and cooling systems and the installed instrumentation are presented. An analysis procedure is briefly described in this chapter and the results are presented in Chapter 4. Some of the contents of this chapter have been presented in an international conference and the paper presented is included in Appendix A.

Chapter 4 presents and discusses the data collected from the monitoring project. The usage hours, total thermal energy provided to the buildings, total electrical energy used and the efficiency from the 10 monitored GSHP systems are briefly presented. The distinct GSHP systems usage patterns from two residential properties were compared further. The results indicate that the infrequent GSHP system use in one of the properties may severely impact the financial and environmental benefits expected through the GSHP system installation. The performance results for the other properties are included in Appendix B.

Chapter 5 utilises the learnings from Chapter 2 and 3. The field data presented in these chapters reveals that Australians use their heating and cooling systems moderately. This leads to the possibility of using hybrid combinations of GSHP and conventional systems. For this reason, this chapter explores the feasibility of utilising hybrid GSHP systems (HGSHP) in Australia as well as in a wider range of climates encountered overseas. Sensitivity analyses of several key design parameters were also conducted to investigate the potential impact on the economic feasibility of hybrid GSHP

systems. The initial analysis for hybrid GSHP systems under Australian climatic conditions have been published in an international conference paper which is included in Appendix A.

Chapter 6 extends the work conducted in Chapter 5. Typically, if a hybrid GSHP system is designed to minimise its lifetime cost, this design is (typically) not the same as the one designed to minimise its lifetime carbon emissions. In this chapter, an HGSHP system design method is proposed with the objective that considers both costs and emissions by using a Pareto optimum approach. Sensitivity analyses for changes in several key design parameters were also conducted for investigating how these changes may impact the economic and environmental benefits of HGSHP systems. This paper has been published in *Geothermics* and included in Appendix A.

Chapter 7 investigates the possibility of connecting hybrid GSHP systems in several buildings into a district configuration (DHGSHP systems). This chapter proposes a methodology to size DGSHP systems. The financial and environmental benefits of DGSHP systems are compared against individual systems for Australian (mostly temperate) climatic conditions. The benefits of combining buildings with different thermal load patterns were investigated as well as the number of buildings to be combined.

Chapter 8 presents the main conclusions of this thesis and includes some recommendations for future research.

The main body of this thesis are supplemented by the following appendices:

- Appendix A: Conference papers published
 1. Full-scale instrumented residential ground source heat pump systems in Melbourne, Australia. A conference paper published in the Proceedings of the 2nd International Symposium on Energy Geotechnics (SEG-2018) in Lausanne, Switzerland. This paper is co-authored with supervisors Associate Professor G.A. Narsilio, Professor I.W. Johnston and Dr M.M. Disfani
 2. Financial assessment of ground source heat pump systems against other selected heating and cooling systems for Australian conditions. A conference paper published in the International Ground Source Heat Pump Research Track conference in Stockholm, Sweden. This paper is co-authored with Dr Olga Mikhaylova, supervisors Associate Professor G.A. Narsilio and Professor I.W. Johnston.
 3. Environmental assessment of hybrid ground source heat pump systems. A journal paper published in *Geothermics*. This paper is co-authored with supervisor Associate Professor G.A. Narsilio,
- Appendix B: Complementary data for chapters 3 and 4: Detailed instrumentation and performance summary for each GSHP systems monitored.
- Appendix C: Python codes used to extract, clean and analyse the field monitoring data collected. In addition, codes to conduct the analysis for HGSHP systems used in Chapter 5, 6 and 7 are also provided.
- Appendix D: Other results from Chapter 5 and Chapter 6.

2 Introduction to ground source heat pump systems in individual and district arrangements

2.1 Overview and structure

This chapter presents a literature review and background related to the research presented in this thesis.

In this chapter, a brief introduction to ground source heat pump (GSHP) system is provided in Section 2.2. Potential benefits for adopting this technology are discussed as well as the barriers to do so. Design methods for GSHP system are also briefly covered here. The review then focuses on experimental works for measuring real-life GSHP system performance.

This flows into Section 2.3 which covers a literature review on hybrid GSHP (HGSHP) system. An HGSHP system is that when a GSHP system is combined with a conventional HVAC system. A GSHP system is typically more expensive to install compared to a conventional system. However, a GSHP system is usually more efficient, which results in lower operational costs than a conventional system. Therefore, an HGSHP system can take advantage of a conventional system's lower installation cost and a GSHP system's lower operational cost, potentially resulting in lower overall lifetime costs to install, maintain and operate the system.

In urban areas, buildings are located close to each other. An individual HGSHP system can be combined with the other HGSHP system in neighbouring building into a district system. This district HGSHP system concept is discussed in Section 2.4, which summarises how district HGSHP system has been utilised worldwide as well as the benefits compared to individual HGSHP system.

Finally, Section 2.5 presents a summary of this chapter. It should be noted that additional and more focused literature reviews have been included in the chapters that contain publications (Chapters 4 through 7).

2.2 GSHP systems

2.2.1 Brief introduction of GSHP systems

Electricity is one of the most dominant energy sources used for heating and cooling residential building in Australia and in the USA [1, 2]. It was reported that 60% of Australian electricity in 2018 was generated from coal [3]. Another report also indicated that the electricity sector is the biggest polluter, which contributes to 33% of the carbon emissions in Australia [4]. This high percentage of coal in the electricity production mix caused Australia to become the fifth most carbon intensive electricity producer in the world [5]. Based on the national average, end users can emit 0.9 kg of CO₂ equivalent per 1 kWh of electricity consumed, which is almost double the OECD average [3].

This carbon intensive electricity consumption should be reduced to achieve a long term environmental sustainability. One such technology that may help in reducing peak energy demand from the grid and associated carbon emissions is that involving GSHP system (also known as shallow geothermal system). GSHP system provides efficient space heating and cooling by using thermal energy from the ground. The popularity of this system has been increasing lately: the total worldwide installed capacity has increased by 34% just between 2010 and 2015 [6].

It is worthwhile to focus some efforts to reduce worldwide carbon emissions in the heating and cooling sector, since it is responsible for about 50% of the energy used in buildings [7, 8] and depending on the source of energy, for about 15 to 40% of associated carbon emissions [4]. Most cities around the world require either heating or cooling (represented by AC – air conditioning) as shown in Figure 2-1 [9]. Furthermore, based on the present climate change data, Gray and Voce [9] predicted that some of the cities below that do not currently require air conditioning will need them in the future. This scenario simply results in a likely increase in carbon emissions in the future from HVAC needs. Therefore, it is valuable to improve our understanding of efficient and renewable energy technologies such as GSHP system in order to mitigate this scenario.

Hot, cold or just right - how does your city measure up?

● Need AC ● Need heat ● Need AC and heat ● Don't need AC or heat

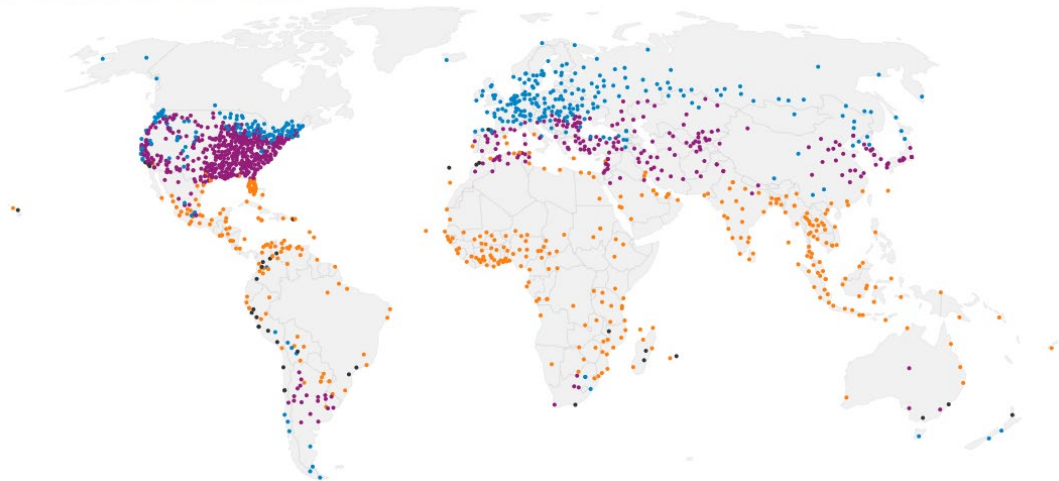


Figure 2-1: Heating or cooling requirements for most worldwide cities (taken from [9])

A GSHP system consists of 3 components: i) the ground loop or ground heat exchanger (GHE), ii) the GSHP itself, and iii) the heating and cooling distribution system the building to be served. The system works by taking advantage of the relatively constant and moderate earth's temperature at a relatively shallow depths (less than ~200 m) to provide heating, cooling and even domestic hot water to a building. In a closed-loop system, heat is exchanged with the ground using a GHE, typically a series of pipes buried underground. For example, during winter, water (or water with antifreeze solution as needed) is circulated inside the GHE and picks up heat from the ground. This heat is then upgraded by the GSHP to provide space heating to the building. In summer, the reverse happens and the ground becomes a heat sink which receives the heat extracted from the building. This process is schematically shown in Figure 2-2. The GSHP is the key component of this process and consist of an evaporator, a condenser, a compressor and an expansion valve. More detailed explanations of the principles of GSHP system have been covered in the literature [10-13] and will not be repeated here.

Closed-loop GHE can be installed in a horizontal or vertical arrangement. A horizontal system is typically installed at about 1 to 2 m depth. It is generally cheaper than a vertical system but requires more land area to install. A vertical system (such as the one shown in Figure 2-2) is the most common in an urban area since it requires a minimum land footprint. However, such system typically requires higher capital costs, mainly for drilling the GHEs. This thesis is mostly focused on the vertical GHE system.

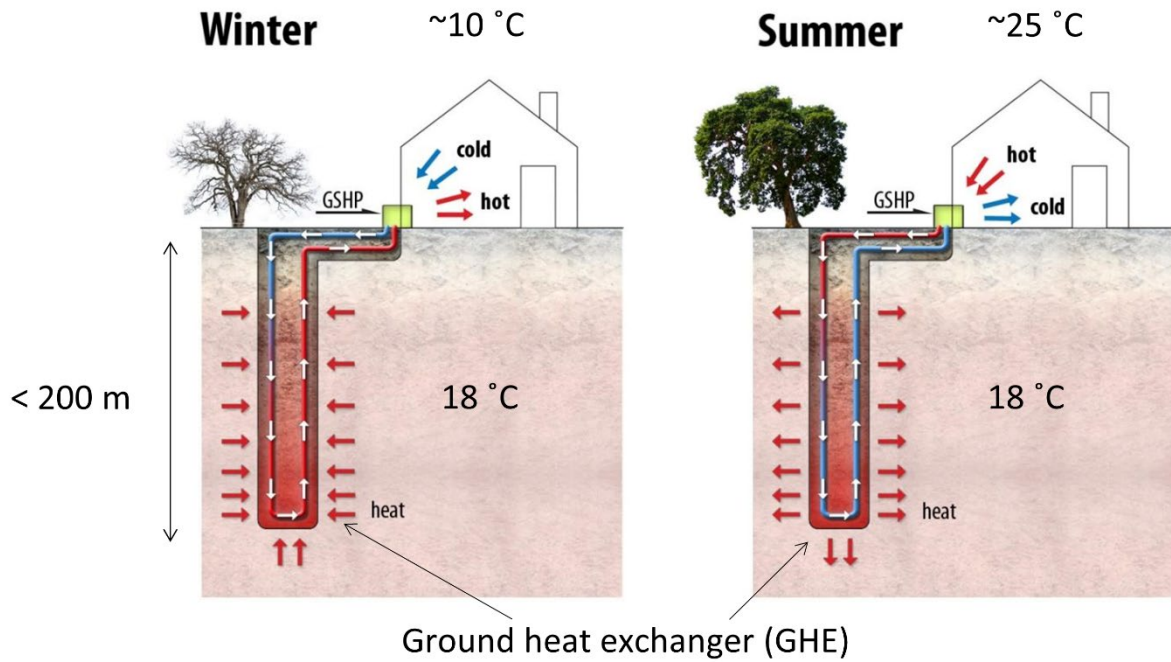


Figure 2-2: GSHP system for heating and cooling (taken from [11])

2.2.2 GSHP system significance and barriers to adoption

Worldwide energy use has been increasing due to an increase in population and global warming. Heating and cooling usage represents about 50% of the energy used in buildings [8]. One way to achieve this is by providing space heating and cooling by using a more efficient system, such as the GSHP system. Efficiency or coefficient of performance (CoP) of GSHP system, defined as the ratio between the thermal energy provided to the buildings in kW and the electrical energy consumed by the GSHP in kW, has been studied experimentally, analytically and numerically [14-22]. A GSHP system typically operates with a CoP of around 3 to 5 [10, 17, 19, 23, 24], which is higher than a conventional system which operates with CoP of 2 to 3 [17, 25-27]. A higher CoP means the system is more efficient and consumes less electrical energy input for equal thermal energy output, which leads to lower electricity consumption, lower operational costs of the system, better financial feasibility, and lower greenhouse gas (GHG) emissions.

For example, a typical 10 kW residential building in Melbourne requires around 34,000 kWh of annual heating and cooling demand. If the conventional system at this house with a CoP of 2.5 is replaced with a GSHP system with a CoP of 4, this will lead to an annual reduction of 5,000 kWh of electricity. This is equivalent to about \$1,400 lower energy bill and 6 tons reduction of CO₂ emissions (or comparable to planting about 42 trees per year).

Additional positive externalities for the use of GSHP system have been well summarised in the literature, such as in the recent work by Brandl [28] and Karytsas and Choropanitis [27]. Karytsas and Choropanitis [27] further classified those benefits in their comprehensive review paper into technological, environmental and socioeconomic benefits, some of which are listed below.

Technological benefits:

- Highly reliable with long lifespan [23, 29-31].
- Lack of an outdoor unit, which can be unattractive and noisy. This also increases the lifespan of the system and reduces maintenance costs [23, 28, 29, 31-33].
- GSHP system has lower risks compared to heating by oil because GSHP system does not require combustion (flameless), fuel storage tank and operate with lower temperature and pressure [28, 29, 31, 33].
- Vertical GSHP system can be minimally influenced by drought, seasonal or daily change compared to a conventional system [28, 34].
- Decreasing peak power requirement [35].

Environmental benefits:

- Lower carbon emissions [24, 28, 31, 33, 36-39].
- Minimal risk during transport or possible ground contamination associated with storing combustible oil or gas in a conventional heating system [31].

Socioeconomic benefits:

- Lower operating costs, maintenance costs and payback period [21, 25, 27, 31, 32, 40, 41]. However, it is important to recognise that these economic indicators are dependent on the alternative heating and cooling systems compared, as well as the energy price.
- Able to contribute to local employment through demand for skilled drillers or installers and also the local economy through job creations and sales of equipment [29].
- GSHP system is less prone to international price fluctuation such as the international oil price or changes in exchange rate [28].

It is also important to recognise that those benefits will not be achieved without best practices for design, installation, operation and decommissioning. The use of a closed-loop system (such as the one in Figure 2-2) along with grouting can minimise the possibility of groundwater contamination [10, 42]. Improper design of GHE may disturb the thermal balance underground, which in turn can affect the long term CoP of the system [11]. Oversizing of some components can also be detrimental to the CoP of the system [22].

Despite these advantages, the number of GSHP systems installed in Australia is much smaller than in other countries such as in the USA, Canada, China and Sweden [6]. Lu et al. [41] reported that the development of GSHP system technology in Australia has been limited by the high capital cost to install the system and limited public awareness. Studies investigating the barriers that limit GSHP system adoption have been carried out, mostly in Greece, UK and USA [43-46]. Karytsas and Choropanitis [27] classified the identified barriers into financial, technical, policy, information and market category. Some of the barriers are quoted below in no particular order [27] :

- High initial investment cost (this is the most cited barrier in the literature).
- Long and uncertain payback period.
- Inadequate financing options.
- Lack of qualified installers, guidelines and reference data.
- Limited space in urban areas.
- Difficulty and high costs for retrofit installation.
- Lack of regulatory framework.
- Unclear requirement to receive grant/subsidy.

- Low awareness for all stakeholders involved, including limited information regarding the costs and benefits.
- Operating cost depends on electricity price.
- Installation cost may be high due to the lack of competition or a markup to account for the unknown in the installation process.
- Limited designers installation experience may oversize the system, leading to higher costs and a decrease in efficiency.

2.2.3 Design methods for GSHP system

The previous section reported that one of the barriers for GSHP system adoption is the lack of guidelines for the design of the system. The design procedure for GSHP system can be complicated. This process includes an estimation of the building's thermal demand, selection of an appropriate heat pump, calculation of GHE length and selection of distribution system. All this process needs to be undertaken properly to ensure GSHP system can perform efficiently to justify their financial viability.

The focus of this thesis is in the calculation of GHE length since GHE length has been reported to make up as much as 50% of the initial investment costs [47] and 24% of the overall costs [22]. There exists various methods for GHE length calculation, such as rules of thumb, various design equations, analytical software and numerical simulations. All of these methods are briefly summarised next.

A rule of thumb is the least accurate [48]. However, a quick estimation of length (and thus costs) can be useful to quickly inform potential homeowners/clients who are interested in the technology. IGSHPA [10]'s rule of thumb suggested that depending on the ground thermal conductivity, 45 to 75 m of GHE is needed for every 3.5 kW thermal capacity installed.

Most design equations and software are based on 3 analytical solutions: the *Infinite Line Source (ILS)* model [49], the *Infinite Cylindrical Source (ICS)* model [50, 51] and the *Finite Line Source (FLS)* model [52, 53]. All three models and their improvements have been reviewed in detail by Yang et al. [54]. The models calculate the heat transfer between the ground and the GHE when a constant thermal load is applied. The main differences between the models are the geometrical assumption. The ILS, CLS and FLS models assume the GHE as an infinite line, an infinite hollow cylinder and a finite line respectively as schematically represented in Figure 2-3 (taken from [55]). The key equations for ILS, CLS and FLS are provided in Equations (1), (2) and (3).

$$T_g - T\left(\frac{r}{2\sqrt{\alpha t}}\right) = \frac{q}{2\pi\lambda} \int_{\frac{r}{2\sqrt{\alpha t}}}^{\infty} \frac{\exp(-\beta^2)}{\beta} d\beta \quad (1)$$

$$T_g - T(F_0, p) = \frac{q}{\lambda\pi^2} \int_0^{\infty} \left[\frac{\exp(-\beta^2 F_0) - 1}{J_1^2(\beta) + Y_1^2(\beta)} [J_0(p\beta)Y_1(\beta) - J_1(\beta)Y_0(p\beta)] \right] \frac{d\beta}{\beta^2} \quad (2)$$

$$T_g - T(r, z, t) = \frac{q}{4\pi\lambda} \int_0^H \left[\frac{\operatorname{erfc}(\sqrt{r^2 + (z-h)^2}/2\sqrt{\alpha t})}{\sqrt{r^2 + (z-h)^2}} - \frac{\operatorname{erfc}(\sqrt{r^2 + (z+h)^2}/2\sqrt{\alpha t})}{\sqrt{r^2 + (z+h)^2}} \right] dh \quad (3)$$

where T [°C] is the ground temperature, at a radial distance r [m], depth z [m] from the ground surface, and at time t [s], when a constant thermal load of q [W/m] is applied per unit length of the GHE. For the ground thermal parameter, T_g [°C] represents the farfield ground temperature, α [m²/s] is the ground thermal diffusivity, and λ [W/(m.K)] is the ground thermal conductivity. In the ICS model, J_n and Y_n are the first and second kind of order Bessel functions, p is dimensionless distance ($p = r/r_b$) and F_0 is the Fourier number ($F_0 = \alpha t/r_b^2$). In the FLS model, the GHE is assumed to have a finite length of H [m].

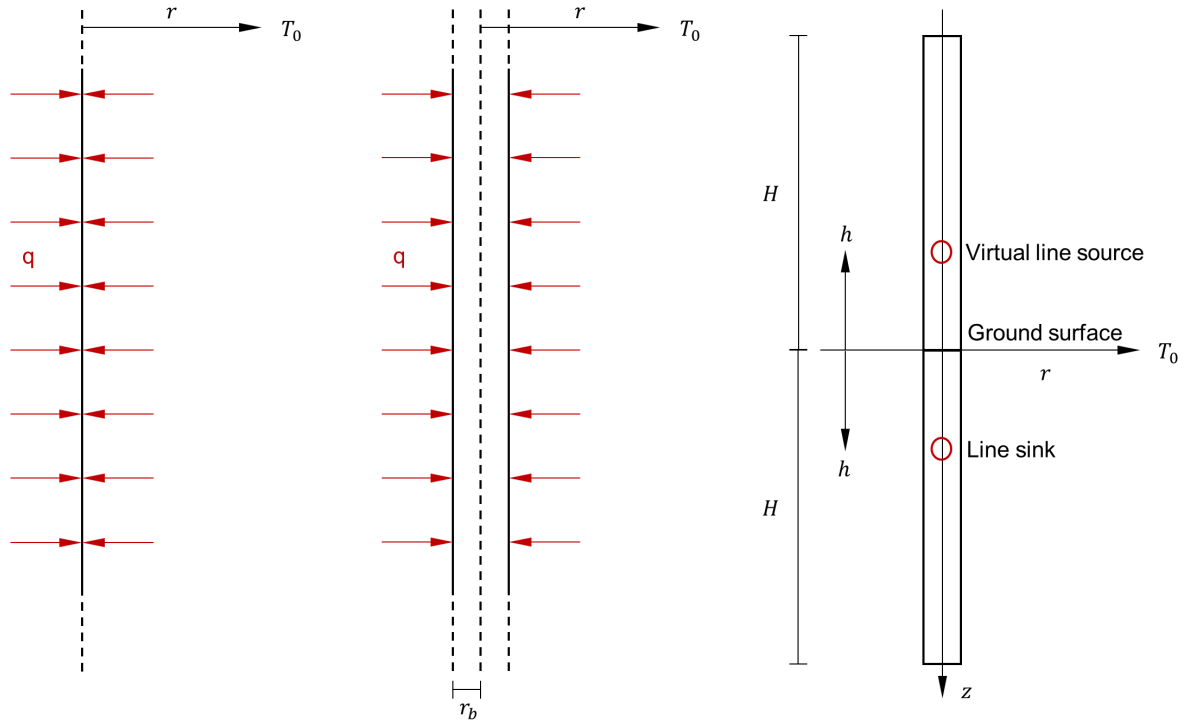


Figure 2-3: Schematic of (a) ILS, (b) ICS and (c) FLS (from [55])

Those analytical models have been adapted into design equations and in commercial software. Two of the most popular design equations are those recommended in handbooks by IGSHA [10] and ASHRAE [56]. The IGSHA design equation was developed at Oklahoma State University based on a simplified ILS model. This design equation only considers the peak heating and cooling demand, which means the transient effect from the long term operation of the system is not considered and may result in deviation from the actual performance of the system [47, 54]. The IGSHA design equation is presented as Equation (4) and (5) to calculate the GHE length [m] required for heating L_H and cooling L_C operations:

$$L_H = \frac{\text{capacity}_H \left(\frac{CoP_H - 1}{CoP_H} \right) (R_B + R_G F_H)}{T_g - \left(\frac{EWT_{min} + LWT_{min}}{2} \right)} \quad (4)$$

$$L_C = \frac{\text{capacity}_C \left(\frac{CoP_C - 1}{CoP_C} \right) (R_B + R_G F_C)}{\left(\frac{EWT_{max} + LWT_{max}}{2} \right) - T_g} \quad (5)$$

where the heat pump's capacity and efficiency in heating and cooling are represented by $capacity_H$ [kW], $capacity_C$ [kW], CoP_H and CoP_C , R_b [m.K/W] is the borehole thermal resistance, R_g [m.K/W] is the ground thermal resistance from the ILS model, F_H and F_C are the run fractions in the heating and cooling design months. The farfield ground temperature is T_g [°C], and EWT_{min} , LWT_{min} , EWT_{max} , and LWT_{max} [°C] represent the minimum and maximum entering (EWT) or leaving water temperature (LWT) at the design conditions, they are the geothermal designer's choice.

The second equation is presented in the ASHRAE handbook and based on the CLS model. This model by Kavanaugh and Rafferty [56] calculates the borehole length by accounting for short, medium and long term thermal pulses. This design equation seems to be the more popular design method used in the literature. However, Cullin et al. [48] have reported that this design equation can yield errors as much as -21% and 167% when compared to the actual installation, but acknowledged that most of the error is due to how the load is represented in the design equation through those three thermal pulses. Other authors have attempted to refine this equation to improve its accuracy, especially when the equation is used for the design of a GHE field (i.e., multiple boreholes) to account for the thermal interferences between GHEs [57-59].

Due to its popularity, this ASHRAE equation is chosen for the analysis conducted in Chapters 5, 6 and 7, specifically the rearranged form suggested by Philippe et al. [60], where GHE length L_{GHE} [m] can be calculated with Equation (6):

$$L_{GHE} = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{T_m - (T_g + T_p)} \quad (6)$$

where q_h , q_m and q_y [kW] are the peak hourly, monthly average and yearly average ground loads, R_b [m.K/W] is the borehole thermal resistance and R_{10y} , R_{1m} and R_{6h} [m.K/W] represent the effective ground thermal resistance for a period of 10 years, 1 month and 6 hours respectively. T_m and T_g [°C] are the mean fluid temperature in the GHEs and the undisturbed ground temperature, T_p [°C] is a temperature penalty and can be assumed as 0 for a single borehole. For multiple boreholes, this correction factor needs to be calculated.

The building thermal requirement needs to be calculated first in order to use Equation (6). The thermal load can be estimated or simulated through commercial software. The building load is then converted into ground load depending on the CoP of the GSHP. The ground load then divided into 3 thermal pulses representing the aggregated load applied to the ground in the short (6 hours), medium (1 month) and long-term (10 years) thermal pulses. Meanwhile, the borehole thermal resistance (R_b) is calculated based on the sum of the thermal resistance of 3 components: the grout, the pipe and the circulating fluid. Philippe et al. [60] presented the equation used to calculate this borehole thermal resistance. The effective ground thermal resistances (R_{10y} , R_{1m} and R_{6h}) are calculated by using the cylindrical heat source solution by Carslaw and Jaeger [50] in respective to the relevant time frame (6 hours, 1 month or 10 years).

Various numerical simulation models have been developed to investigate the heat transfer in various GHE configurations. Tools such as TRNSYS [61], ABAQUS [62] and COMSOL [55, 63] have been used for some of these numerical models. A numerical model is generally regarded as the most accurate in the literature but limited by the long computational time which makes it hard to incorporate in GHE design in every day engineering practice [54]. Demand for these numerical models is expected to increase with the increase in popularity of the increasingly complex geometry in energy geostructures [55, 64-66].

2.2.4 Full-scale monitoring of GSHP system

Even though approximately 6 million GSHP systems have been installed worldwide, experimental studies and real-life performance on GSHP systems are still limited. Lack of reference data regarding systems performance, costs and benefits have been cited as one of the challenges for GSHP systems adoption [20, 27, 31, 40, 43, 67]. This lack of data further limits the awareness of this technology amongst all of the stakeholders involved [27]. Therefore, full-scale monitoring, creation of demonstration sites and increasing the availability of GSHP system information have been identified as some of the diffusion actions required [27].

In general, energy performance for buildings is measured based on their energy use intensity (EUI), which is typically expressed as thermal energy per unit area [kWh/m^2]. EUI data is simple to gather, usually by using energy bills and space conditioned area. Li et al. [68] reported that the EUI of conventional systems can vary significantly from their measurement in 51 high-performance buildings throughout the USA, Europe, Asia and Australia. A report by the Electric Power Research Institute [69] indicates similar EUI trend from the GSHP systems used in 35 commercial buildings in the USA. Recently, Spitler and Gehlin [20] noted that analysis using EUI measurement can lead to difficulties in assessing energy inefficiency and encouraged more detailed monitoring of heating and cooling system performance. However, they also recognised that even if such data is collected, the lack of data availability in the literature prevents a detailed comparison study with the performance of a similar building [20]. Therefore, one contribution of this thesis is to provide such monitored data for several GSHP systems performance in the greater Melbourne area and other parts of Victoria under several distinct user behaviours.

Although limited, there has been several GSHP systems monitoring projects worldwide, mostly in Europe and the USA. One common trend observed in Europe is that different methods to report efficiency were used across many projects, which make it difficult to compare the efficiency of GSHP systems between projects or when compared with conventional systems [70]. Gleeson and Lowe [70] have noted that those differences are due to the different system boundaries used. One of the most common efficiency descriptions used in literature is one defined in the SEPEMO project [71], where there are four different versions of seasonal performance factors (SPFs). The SPF is the ratio of thermal energy output compared to the thermal energy input. A satisfactory GSHP performance is typically represented by an SPF of around 4 [10]. An SPF of 4 means 1 kWh of energy input (electricity) is required to provide 4 kWh of thermal energy (heating or cooling).

The energy input may include the power consumption of the heat pump itself (SPF_1), plus the ground side circulation pump/fan (SPF_2), plus the backup heater (SPF_3) and plus the building side circulation pump/fan (SPF_4). In the literature, SPF is typically used to measure average efficiency overtime, usually yearly, while CoP is used for a shorter timeframe [20].

Experimental studies worldwide

Gleeson and Lowe [70] presented an extensive summary from over 200 residential GSHP systems installed in Austria, Denmark, Germany, Sweden, Switzerland and the UK prior to 2013, where the SPF_4 varied between 1.4 and 5.1. Part of this data set is from a field trial in Germany where some new buildings were equipped with GSHP systems and some with air source heat pump (ASHP) systems, with an average SPF_4 of 3.75 and 2.74 respectively [72]. In the SEPEMO project, Nordman et al. [71] reported SPF_3 between 2 and 7.3 from 29 residential GSHP systems in Austria, France, Germany, Greece, Netherlands and Sweden. Over half of those monitored installations have SPF_3

greater than 4 and monthly SPF₃ are provided for some case studies. Other smaller single house studies have been conducted with examples include CoP of 3.4 in France [73] and CoP of 3.2 in the USA [21].

GSHP system performance in commercial systems or multi-residential buildings is generally more complex but have generated much bigger interest to be monitored in detail. Recently, Spitler and Gehlin [20] provided a comprehensive summary for monitored commercial GSHP systems, especially those that had been monitored for long-term. They summarised that a heating SPF₄ between 1.2 and 4.7 and a cooling SPF₄ between 2.8 and 7 were observed from various literature sources. One thing to note is that only 24 out of 55 datasets cited by Spitler and Gehlin [20] reported their performance in daily (or lower) resolution. This suggests there is a need for more detail GSHP systems performance which may help to identify and diagnose poor GSHP systems performance.

Comparisons between GSHP and conventional systems have been covered in some literature. GSHP systems consume less energy than conventional systems [74], have lower annual costs [75], perform at higher CoP [76, 77] and emits lower GHG [21]. Bloom and Tinjum [21]'s experiment further indicates that GSHP systems have 8 year payback period against similar-sized conventional systems. However, it has been reported that if the ground/subsurface conditions are not considered carefully, the GSHP systems are often under or over-designed, thus affecting the long term financial feasibility of the systems [78]. This further reinforces the need to collect more experimental data of such systems under different climate and geological conditions.

Experimental studies in Australia

Although several GSHP systems have been installed in Australia, many of them do not have any monitoring system installed or if they do, the data is not publicly available. The following is a summary of full-scale monitored GSHP systems available in Australia:

- Geoscience Australia building in Canberra [79]. The 10-year review indicates that the GSHP system reduces energy consumption and saves \$40,000 per annum.
- Elizabeth Blackburn School of Sciences in Victoria [80-84]. Mikhaylova [80] reported that daily system's CoP was observed to be around 3.4 in heating and 2.5 in cooling.
- Sustainable Building Research Centre in the University of Wollongong in New South Wales [25] with operational CoP around 3.
- An aquatic centre in Western Australia [85], where the project was reported to reduce gas consumption by 618 GJ (worth \$21,000) in the first month of operation.
- Kivi [86] monitored GSHP performance in an office building at the University of Melbourne. A CoP of as low as 1 and as high as 7 were observed depending on whether the GSHP operated with partial or peak capacity.
- Kivi [86] also monitored a GSHP system performance in a 700 m² residential house and reported a CoP of around 3 from 2 GSHPs used to provide a constant heat flux for pool heating
- Lu et al. [87] reported an average CoP of 3.1 for a 20 kW system for 20 days of operation period at the University of Queensland's J.K. Murray library.
- Although there has been no data collected at the time of writing, Zhou et al. [88] are in the process of conducting full-scale monitoring of GSHP system for heating a poultry shed with 10,000 chicks in New South Wales.

All of the above works monitor commercial systems, except one residential system by Kivi [86], and even then that is for a residential house with a much larger floor area than the typical. Furthermore, Kivi [86] also noted that assessing the real-life systems' performance can be difficult because of the thermal requirement variability by the occupiers, which results in variable heat flux to the GHEs. This suggests a research gap to provide data and analysis for GSHP systems performance for real-life demand usage in typical residential buildings.

Other GSHP systems related experiments or field data collection have been performed, such as measurement of ground temperature around Australia [79, 80, 85-87, 89-92], thermal response tests (TRT) [86, 87, 89-91, 93, 94], thermal charging of GHEs using solar collectors [95, 96] and investigation in energy geostructures, such as energy piles [89, 91, 94]. All these works have increased the overall understanding of GSHP systems and improve the awareness of such technology in Australia.

In terms of financial feasibility studies, Lu et al. [41] provide a comprehensive economic analysis for vertical GSHP systems in Melbourne. This study shows that capital costs for GSHP systems are still high under the current Australian cost conditions. Furthermore, a GSHP system has a simple payback of 20 years against a conventional HVAC system under current high-cost conditions.

2.3 Hybrid GSHP systems

Section 2.2 has summarised that GSHP systems typically are more efficient than conventional systems, but require higher capital costs, which results in high lifetime costs and payback periods. One strategy to reduce these costs and payback periods is to utilise a hybrid ground source heat pump (HGSHP) system. HGSHP systems consist of GSHP systems to provide the base-load thermal demand and are supported by conventional systems to top-up for the hotter and colder period of the year. This way, HGSHP systems can benefit from both a conventional system's lower installation costs and a GSHP system's lower operational costs [97-99].

The idea behind HGSHP system comes from the fact that the peak thermal demand only occurs for several hours of the year. For a conventional system, the heating and cooling unit simply needs to have a larger rated capacity than this peak thermal demand. In contrast for GSHP system, this peak thermal demand determines the length of GHE needed and this GHE is typically the most expensive component of a GSHP system [27, 41]. For this reason, it may be beneficial to size the GSHP system lower than the peak thermal demand and only provide the baseload demand. This system is then supported by a conventional system with lower installation costs for use during those few hours of the year where the peak demand occurs. The proportion of the peak thermal load to be provided by the GSHP system is typically called a *shave factor* [98, 100]. In this thesis, a *shave factor* is defined as the ratio between thermal load provided by the GSHP and the total thermal load requirement. So, an 80% shave factor in a 10 kW system means the GSHP provides 80% of the peak thermal load (8 kW) while a conventional system provides the remaining 20 % (2 kW).

This is illustrated below in Figure 2-4, where if a GSHP system in Sydney is sized to provide 50% of the peak heating and cooling load, then the GSHP system can meet around 83% of the annual thermal demand. With this hybrid configuration, a 10 kW system in Sydney requires only 167 m of GHE length. This can be compared to a GHE length requirement of 265 m in Sydney if 100% of the peak load is to be satisfied by the GSHP system. The HGSHP system can be deemed financially

beneficial if this drilling cost savings is higher than the additional costs generated from installing and operating the auxiliary lower efficiency conventional system.

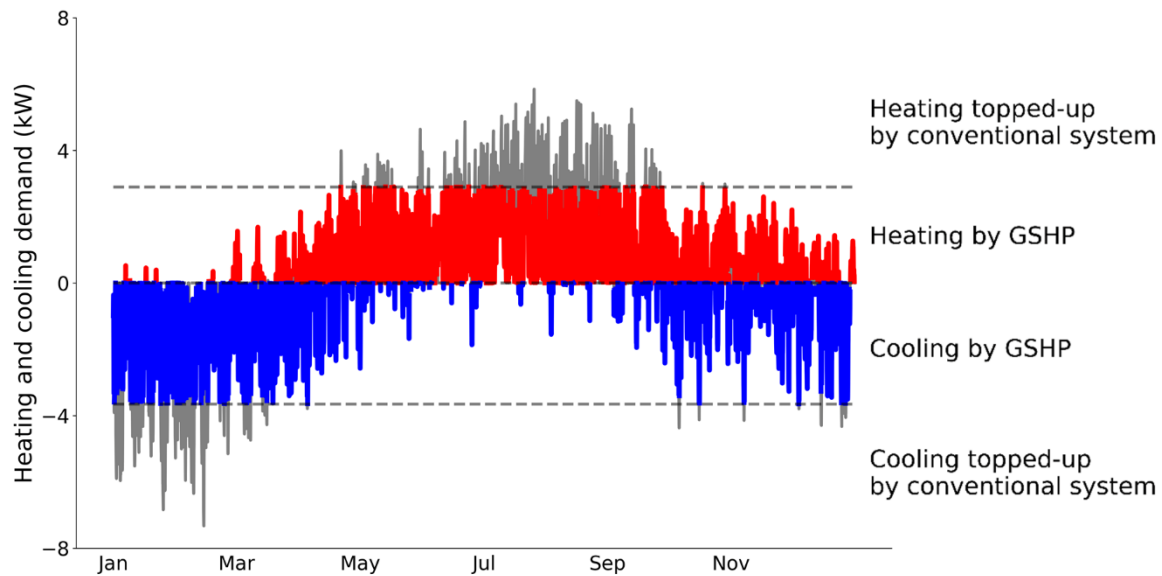


Figure 2-4: An example of an HGSH system in Sydney sized to meet 50% of the peak heating and cooling power demands (i.e., a shave factor of 0.5)

Studies related to HGSH systems have gained popularity in recent years, both numerically and experimentally, such as in [97-104]. Qi et al. [103] defined HGSH system as a GSHP system with an additional heat source or heat sink. Examples of some additional heat source are solar collectors and gas boilers, while additional heat sink such as cooling tower or pavement heating system can be used. Furthermore, this additional heat source or sink in HGSH system can be used to minimise potential ground temperature change for buildings with a high unbalanced thermal demand [103].

Two notable review papers have summarised the current status of HGSH system adaption worldwide and noted that HGSH systems are widely used in Europe and North America [54, 103]. Some examples of buildings with HGSH systems available are in the USA [105], Sweden [106], France [73], Turkey [107], Korea [108] and China [103, 109]. Various numerical and experimental studies in HGSH systems reported that HGSH systems can reduce GHE length requirement [110], have higher CoPs [108] and lower lifetime costs [110, 111] compared to traditional GSHP systems.

Qi et al. [103] also recommended using a hybrid coupling between GSHP and ASHP system for moderate climate regions. Following this recommendation, the considered conventional systems in this thesis are ASHP system and gas furnace. This assumption is further justified since they are also the most common conventional heating and cooling systems used in Australia [1].

2.4 District GSHP systems

In urban environments, buildings are often located in close proximity which allows the possibility for district use of GSHP systems (DGSHP systems). In DGSHP systems, multiple buildings are connected to systems of GSHPs, through a common water loop between each individual building. The system can be further improved by utilising the hybrid system concept (i.e., HGSH systems), where the

GSHP systems can be supported by conventional systems during the hotter and colder day of the year.

A schematic of GSHP systems in individual and district arrangement are presented in Figure 2-5. Each one of the individual buildings in Figure 2-5 (left) has a 10 kW GSHP system installed and supported by an ASHP. The other houses with the DGSHP system are connected to a 20 kW GSHP system. Imagine the case when one of the buildings has its occupants at home and requires a 15 kW heating demand, whereas the occupants of the other buildings are away. For the individual system, this means that the GSHP system can provide only 10 kW heating and the ASHP (conventional system) is used to provide the remaining 5 kW. For the district system, the present occupiers can use the GSHP system to provide the whole 15 kW demand without the need to use the ASHP system. Although the total thermal load is the same between both systems at this particular time (15 kW), the DGSHP system requires less electrical energy because all the thermal load is provided by GSHP system, which is more efficient than the ASHP system. Therefore the DGSHP system should have a lower operating cost in this idealised example.

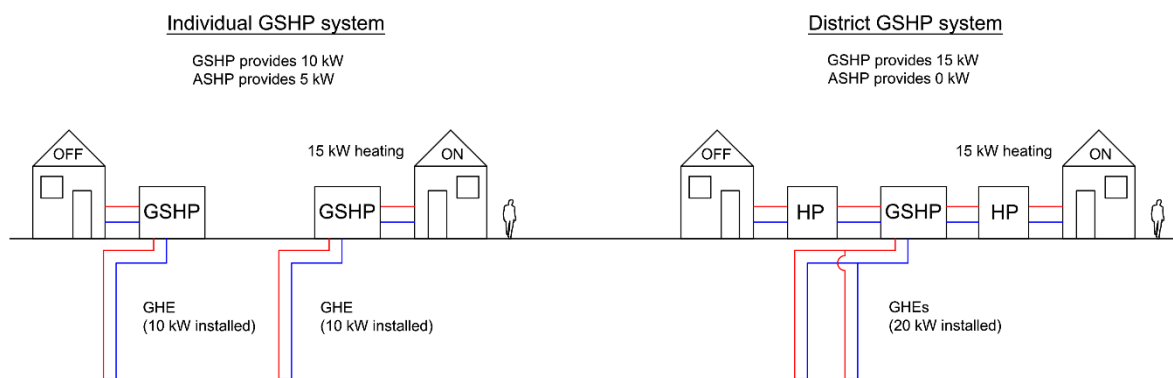


Figure 2-5: schematic of individual (left) and district (right) GSHP systems

Buildings can also help to indirectly heat and cool each other in DGSHP systems configuration [100]. If one building requires cooling, it can reject the heat from the building via their own heat pump (“HP” in Figure 2-5) into a common water loop. This heat can be extracted by a heat pump in another building for the heating demand in the second building. An example of this idealised scenario is in a sport centre where a gym that requires cooling for most of the year is located next to a swimming pool that requires heating for most of the year.

This is similar to how air conditioning zoning works in commercial systems. In this extreme (and rare) scenario, the thermal load required between both buildings can balance each other, and does not require the use of the GSHP to extract or reject energy from/to the ground. Most other times, the thermal energy available in the common water loop is not enough to meet the entire thermal demand for the district system. In this case, the additional thermal energy is extracted (or rejected) from (or to) the ground via the common GSHP and ground heat exchangers (GHEs). If needed, further auxiliary thermal energy is available from top-up conventional systems (ASHP in this example). The highest savings occur when a heating and cooling dominant buildings are combined [100]. This will lead to a reduction in GSHP system maximum capacity needed and GHE length required, which will further decrease the capital costs of the system and increasing the financial feasibility of utilising this GSHP systems technology.

The reasons described above have led to an increase in studies to estimate GSHP systems potential for cities worldwide [112]. Researchers have attempted to estimate the urban geothermal potential in the USA, UK, Switzerland, Italy, Spain, Germany, Argentina, China and Australia, among others [113-120]. One interesting study by Zhang et al. [115] reported that utilising combination of 150 m GHEs installed around the city may be able to provide up to 24 and 100 times of the annual heating demand in London and Beijing respectively. The potential to use tunnel linings as GHEs to provide heating and cooling to residential buildings along the tunnel route has been investigated in London, Torino and Jenbach [121-123]. However, the use of DGSHP systems may have an adverse impact. Alcaraz et al. [119] described that if a significant amount of thermal energy is extracted or injected to the ground in area with a high groundwater flow, this may cause a thermal plume interference, which may deteriorate the performance of neighbouring GHEs.

Despite all these studies worldwide, the investigation of DGSHP systems is still limited in Australia, except one by Pujol et al. [120], who estimated a potential heat extraction thermal energy between 110,000 and 180,000 GJ annually from an aquifer in Perth, Western Australia.

This thesis aims to contribute to the lack of such investigation in the literature, specifically for Victoria's temperate climatic conditions. The local climatic condition in greater Melbourne indicates that most residential buildings are heating dominant. This provides an opportunity to be combined in a district arrangement with cooling dominant commercial buildings. Furthermore, the investigation of DGSHP systems under Melbourne climatic conditions is important because there has been a plan for several large infrastructure developments with the potential to use such systems. Examples of such projects are the Melbourne Metro Tunnel project, Western Distributor Tunnel Project and Fishermans Bend area development (the largest urban redevelopment plan in the country).

2.5 Summary

The literature review related to this research is presented here, focusing on experimental, hybrid and district GSHP systems. GSHP systems can be used to provide sustainable heating and cooling, and typically has lower lifetime costs and emissions compared to conventional systems. Despite this, the adoption of such system is still limited due to various reasons. One of which, is the lack of information and data regarding real-life performance of the system, especially for residential buildings in temperate climatic condition, such as in greater Melbourne.

Another barrier for GSHP systems adoption is the high capital costs requirement. One way to address this is by using hybrid GSHP systems. This system can be further connected with other hybrid GSHP systems nearby to form a district system. District system can be beneficial under Melbourne climatic conditions because the peak thermal demand only occurs for a few hours of the year. Furthermore, under this climatic condition, it can be beneficial to combine heating dominant residential buildings with cooling dominant commercial buildings. Present literature indicates that such configuration is getting traction worldwide and can enhance the benefit of traditional GSHP systems.

This thesis aims to contribute to this literature gap by providing real-life monitored GSHP systems performance in Victoria and particularly greater Melbourne. Furthermore, the economic and environmental feasibility of hybrid and district GSHP systems are investigated to increase our understanding of those systems.

3 Residential GSHP systems monitoring project in Melbourne, Australia: experimental setup and analysis procedure

3.1 Introduction

To achieve the first objective of this research work, a full-scale experimental study to monitor the performance of Ground Source Heat Pump (GSHP) systems under various dwelling sizes, patterns of usage, geologies and local weather conditions in Melbourne was proposed. The study was funded by the Victorian Government since 2012 and called the Sustainable Energy Pilot Demonstration (SEPD) project [12, 124].

The original aim of this SEPD project was to monitor the GSHP systems performance in 40 residential properties around Melbourne. However, the final number of monitored project is about half of this due to the difficulties of obtaining projects and construction challenges. Nevertheless, 23 properties were part of this SEPD project and good quality data were obtained. This thesis presents the analysis results from the data collected from 10 of these properties.

It should be noted that the author was employed as a research assistant for this SEPD project for 3 years prior to undertaking this PhD program. The author's main responsibilities were to manage, supervise installation and instrument the GSHP systems. During the PhD candidature, the author continues to complete installation and instrumentation, replaces sensors when they malfunctioned, collects performance data as well as performs analysis on the data regularly. Most of the data analysis was conducted during this PhD period, hence it is appropriate to include the insights and learnings from those data as part of this thesis.

This chapter describes the experimental set up in the SEPD project, including locations and geologies of the monitored properties, ground heat exchangers, indoor heating and cooling components, and the instrumentations installed. Furthermore, the analysis procedure conducted in this study is also briefly described here, while the results of this unique full-scale experimental setup are presented in Chapter 4. A summary of this chapter has been presented in an international conference, and the conference proceeding is attached in Appendix A. A sample Python code used for the analysis briefly described in this chapter is provided in Appendix C.

3.2 SEPD project: experimental setup

3.2.1 Location and geology of the properties

The SEPD project has been running since 2012 and involved with the collection and assessment of key parameters needed for studying typical GSHP systems performance in greater Melbourne. There are 23 properties as part of this project and they are located throughout Victoria. However, due to some instrumentation problems, project delays and other unknowns, only 10 of those properties managed to produce high-quality datasets which are sufficient for a detailed analysis study. The location of these 10 properties is shown in Figure 3-1. The data and experimental setup from the 23 properties are included as much as possible in this thesis for completeness, but only the analysis results of the 10 properties listed in Figure 3-1 are presented. The analyses presented in this thesis cover at least more two year of monitoring period.

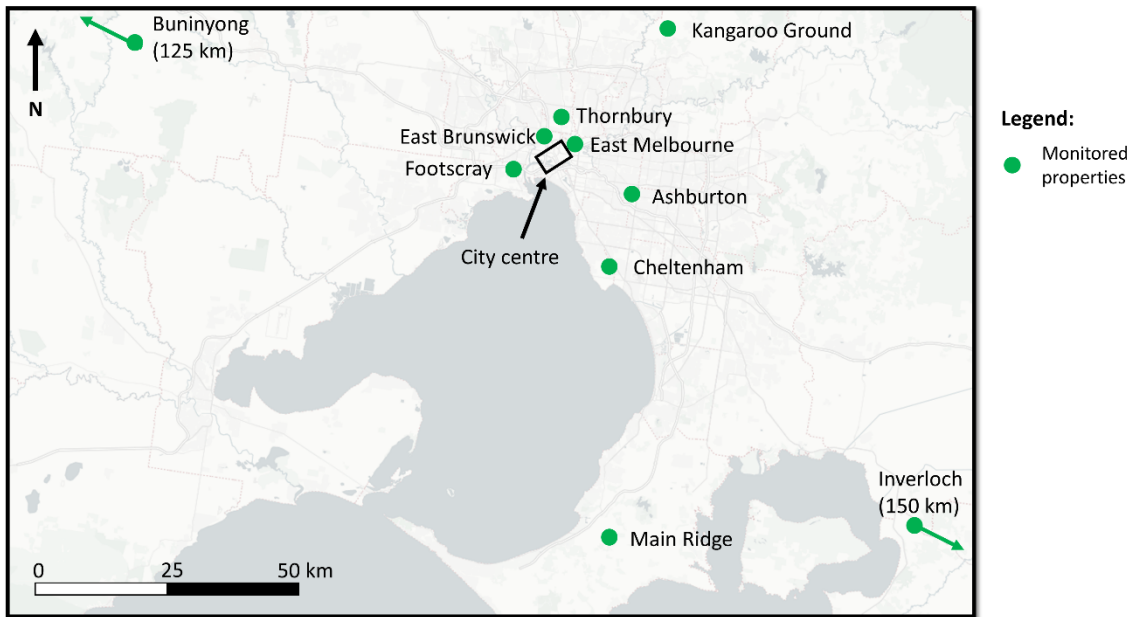


Figure 3-1: Monitored properties under the SEPD project

The diverse location shown in Figure 3-1 is expected to be able to give an indication of typical weather conditions and geology formations typically encountered around greater Melbourne. Table 3-1 summarises the distance of these properties from Melbourne CBD along with their geologies based on the geological maps of Melbourne [125].

A good GSHP system design requires the accurate estimation of ground thermal properties at each site, such as the ground thermal conductivities, undisturbed ground temperature, borehole thermal resistance and ground heat capacity. Mikhaylova et al. [82] described that ground thermal conductivity greatly affects the GHE design length and thus, the financial viability of the project. Projects located at different geologies will have different soil composition. Thermal conductivity of soil can vary greatly between 0.7 – 3 W/m.K and can be affected with the presence of groundwater table and ground water flow [93, 126]. Unfortunately, the availability of these ground thermal properties information is still limited in Australia due to the relatively young geothermal industry at this stage.

The locations presented in Figure 3-1 include three dominant geology formations typically found in the area: the Melbourne Formation, the Brighton Group and the Older Volcanics. These three geologies cover most of the greater Melbourne area which means that future GSHP system projects will likely fall within these ground conditions. Therefore, the data collected in this project will contribute immensely to the understanding and design of future GSHP system installations in Melbourne.

The measurement of the undisturbed ground temperature and ground thermal conductivity in some of these locations were conducted and has been reported in Jensen-Page [93] by conducting a thermal response test. This test consists of injecting a heated water through the GHE and measuring the development of the inlet and outlet temperature over time. This test was conducted at Cheltenham 1, Cheltenham 2, East Brunswick, Footscray and Thornbury.

Table 3-1: Locations and geology of the monitored properties under the SEPD project

Project location/suburb	Distance from Melbourne CBD (km)	Geology ³
Ashburton ¹	25	Tpr - Brighton group - red bluff sand, with siltstone and sandstone
Buninyong ¹	125	Oll - Castlemaine supergroup - deep marine deposits, sandstone
Carlton ²	2	Sud - Melbourne formation - sandstone & siltstone
Cheltenham 1 (residential) ¹	20	Tpr - Brighton group - red bluff sand, with some clay
Cheltenham 2 (commercial) ²	20	Tpr - Brighton group - red bluff sand
Daylesford ²	110	Och - Castlemain group - sandstone
East Brunswick ¹	7	Qvn - Newer volcanics - basalt
East Melbourne ¹	3	Qvn - Newer volcanics - basalt
Ferntree Gully ¹	40	Dvf - Gerny creek Rhyodacite
Footscray ¹	10	Qvn - Newer volcanics - basalt
Frankston ²	50	Ou - Sandstone
Inverloch ¹	150	Kls - Wonthaggi formation - sandstone, siltstone, coal
Kangaroo Ground 1 ²	35	Sla - Anderson creek formation - siltstone
Kangaroo Ground 2	35	Sla - Anderson creek formation - siltstone
Main Ridge ¹	85	Ov - Older volcanics - basalt
Mildura ²	540	Qw - Woorinen formation - dune sand, calcareous clayey
Monbulk ²	50	Tvo - Olivine basalts
Mulgrave ²	30	Qra - Alluvium
Murrindindi ²	100	Suy - Yea formation - sandstone & siltstone
Parkville ²	2	Sud - Melbourne formation - sandstone & siltstone
Thornbury ¹	10	Sud - Melbourne formation - sandstone & siltstone
Toorak ²	8	Tpr - Brighton group - red bluff sand
Wangaratta ²	250	Qs – Shepparton formation

¹ Properties with a high-quality dataset and presented in this thesis

² Properties that have not been completed or analysis is limited due to low-quality data

³ Symbols associated to local geology and age, as per Geological Maps of Victoria.

3.2.2 GHEs, GSHPs and HVAC systems installed in the SEPD project

This section describes the ground heat exchangers (GHEs), ground source heat pumps (GSHPs) and heating, ventilation and air conditioning (HVAC) systems installed in the 23 properties of the SEPD project.

In closed-loop systems, GHEs comprise pipes embedded in specifically drilled boreholes or trenches or even built into foundations. Most of the circulating fluid used in this project (and the most common in the world) is water. Despite that, the SEPD project also monitors two properties which have copper loops installed, with refrigerant as the circulating fluid. This is not commonly used and usually avoided due to the risk of leaking refrigerant into the ground and water table. Unfortunately, the instrumentation installed in these two properties were lacking, which prevented detailed analysis of the performance of the systems. A comparison between water and copper loop systems have been conducted in the literature, such as by Colls [89], who observed that copper loops have similar or sometimes slightly lower efficiency compared to water loop systems.

The most common GHEs installation used in the SEPD project is the vertically drilled boreholes, especially for those properties located in urban areas with limited land space. The typical vertical GHE installation depth in this project is 50 m, but there is a project with GHE installed as deep as 90 m. Alternatively, GHEs can be installed in trenches with horizontal configurations. This horizontal GHEs are cheaper to install but require a larger land surface area. These makes horizontal GHEs only typically suitable (and installed) in rural areas such as those at Kangaroo Ground, Main Ridge and Buninyong. Finally, the property in Monbulk utilises energy piles where geothermal pipes are embedded into subsurface structure, in this case, building's foundations. These monitored energy piles in Monbulk is the first measured energy geostructures in Victoria for a real-life thermal load. A summary of the GHE type and geometry installed in each of the properties is presented in Table 3-2.

A GSHP is needed to extract or reject thermal energy to or from the building. The main components required inside a GSHP are compressor, condenser, evaporator and expansion valve, as describe in the previous chapter. At the beginning of this project, there was no known GSHP manufacturer in Australia and a number of GSHPs needed to be imported from established manufacturers overseas. Importing a GSHP requires a long lead time associated with the assembly, testing and delivery to Australia. For this reason, several locally manufactured heat pumps (found later on) were also trialled in this project. The performances of these locally manufactured heat pumps turned out to be significantly lower than the heat pumps made by established manufacturers from overseas. This is due to the limited research and development that has been put to these local GSHPs along with the difficulties to source the required components locally. GSHPs of various sizes are used in this project, with GSHP capacities varying between 6 and 30 kW. The GSHPs used in each property are summarised in Table 3-2 and the locally manufactured heat pumps are clearly identified. Note that a water to water GSHP refers that water is the heat exchange fluid inside the GHE and water is also used as the heat exchange fluid in the HVAC distribution system. Similarly, a water to air GSHP refers to water inside GHE and air is used as the distribution system.

The HVAC distribution systems used in this project are not the focus of this thesis. Despite that, it is important to recognise that various HVAC systems were tried to be utilised with the GSHP systems in this SEPD project. This project has proven that the GSHP is compatible with various HVAC systems typically found in Melbourne as summarised in Table 3-2 below. The HVAC distributions systems used in this project are floor hydronic, wall hydronic panel, fan coil unit (FCU) and ducted air conditioning. The hydronic panel heats the room by using a radiator system, installed inside the floorboard or as a panel on the wall. The fan coil unit used here is typically a split system, which

provide heating and cooling by blowing fresh air over a chilled water or hot water coil. A ducted air conditioning distributes cool or warm air through a series of ducts within the property. Furthermore, the GSHP systems in some of the properties are also used to heat water for domestic hot water consumption, pool or spa heating.

Figure 3-2 presents selected pictures of the GSHP systems throughout the installation period, one can see the various types of GHEs, GSHPs and data loggers used for data collection.

3.2.2 General installation procedure

In general, the following describe briefly how the project was chosen, as well as the installation and instrumentation procedure.

1. Interested parties contacted the research group at the University of Melbourne.
2. A team from the University and our project partner conducted a site visit to assess the possibility. Factors assessed including the size of the house, location of the house, space availability for GHE installation as well as for a potential plant room for the GSHP unit and the data logger.
3. The University's team and/or project partners conducted design of GSHP systems based on available information and procurement of equipment (such as GSHP unit). In the case of limited information, the best "guesstimates" were used based on the installers experience and available literature.
4. The University's team decided on instrumentation (see Section 3.3 for detail) and responsible party to procure them.
5. The project partners or their contractors installed the GSHP system. Starting with drilling the GHEs, installation of the header pipes, installation of GSHP unit in the plant room, installation of the appropriate HVAC system and commissioning of the overall heating and cooling system.
6. The University's team installed the instrumentation with the help of contractors or directly via contractors.
7. Property owners give feedback to the University's team and project partners regarding the performance of the systems. Sometimes this leads to adjustment and maintenance of the systems.
8. The University's team was responsible for data collection overtime (online and offline). Whenever the instrumentation equipment breaks down, they are to be replaced if possible.



Drilling of a vertical GHE at Thornbury



Vertical GHE installation at Thornbury



Slinky GHE at Main Ridge



Installation of pond loops at Murrindindi



GSHP and data logger at Kangaroo Ground 2



GSHP and circulation pumps in the roof attic at Cheltenham 1

Figure 3-2: Selected pictures from the SEPD project installations

Table 3-2: Summary of GHE, GSHP and HVAC distribution systems installed in the monitored properties under the SEPD project

Properties location	Number, orientation ³ , total GHE length (m)	GSHP ^{4,5,6} heating/cooling capacity installed (kW)	HVAC systems installed
Ashburton ¹	4, V, 360	⁴ 32/28	Floor hydronic heating, FCU ⁷ for cooling, water and pool heating
Buninyong ¹	4, H, 160	^{4,6} 8/8	FCU for heating and cooling
Carlton ²	20, V, 1,000	⁴ 9 GSHPs, each 38/34	Ducted heating and cooling
Cheltenham (residential) ¹	2, V, 110	⁵ 6/9	Ducted heating and cooling
Cheltenham (commercial) ²	2, V, 120	⁴ 8/9	Hydronic panel on the wall and FCU for heating and cooling
Daylesford ²	3, V, 160	⁴ 8/8	FCU for heating and cooling
East Brunswick ¹	2, V, 130	^{4,6} 8/8	FCU for heating and cooling
East Melbourne ¹	2, V, 12-	⁴ 11/9	Ducted heating and cooling, water and spa heating
Ferntree Gully ²	3, V, 165	⁴ 2 GSHPs, each 12/12	FCU for heating and cooling and hot water
Footscray ¹	2, V, 110	⁵ 8/10	Ducted heating and cooling
Frankston ²	9, S, 220	⁴ 22/17	Floor hydronic heating, FCU and hot water
Inverloch ¹	6, V, 300	⁴ 18/17	Floor hydronic heating and cooling & hot water
Kangaroo Ground 1 ²	6, CL, 180	⁴ 14/14	Hydronic heating and FCU for cooling
Kangaroo Ground 2 ¹	9, S, 320	⁴ 16/15	Hydronic heating and FCU for cooling
Main Ridge ¹	8, S, 320	⁴ 22/17	Hydronic heating systems and hot water. No cooling
Mildura ²	2, V, 130	⁵ 6/6	Ducted heating and cooling
Monbulk ²	27, EP, 81	⁴ 2 GSHPs, each 20/20	Hydronic heating and FCU for cooling
Mulgrave ²	3, V, 100	Project abandoned	Project abandoned
Murrindindi ²	4, H, 200 & 4, PL, 400	⁴ 13/9	Ducted heating and cooling

¹ Properties with a high-quality dataset and presented in this thesis

² Properties that have not been completed or analysis is limited due to low-quality data

³ V = vertical GHEs, H = horizontal GHEs (straight pipe), S = horizontal GHEs (slinky), CL = copper loops, EP = energy piles, PL = pond loops

⁴ Water to water GSHP

⁵ Water to air GSHP

⁶ Experimental GSHP manufactured locally

⁷ Fan coil unit

Properties location	Number, orientation ³ , total GHE length (m)	GSHP ^{4,5,6} heating/cooling capacity installed (kW)	HVAC systems installed
Parkville ²	5, V, 250	⁴ 32/28	FCU for heating and cooling
Thornbury ¹	2, V, 100	^{4,6} 6/6	FCU for heating and cooling
Toorak ²	15, CL. 450	⁴ 2 GSHPs. Each 21/21	Hydronic heating and FCU for cooling & hot water and pool heating
Wangaratta ²	6, V, 450	⁴ 21/21	Hydronic heating and hot water

¹ Properties with a high-quality dataset and presented in this thesis

² Properties that have not been completed or analysis is limited due to low-quality data

³ V = vertical GHEs, H = horizontal GHEs (straight pipe), S = horizontal GHEs (slinky),
CL = copper loops, EP = energy piles, PL = pond loops

⁴ Water to water GSHP

⁵ Water to air GSHP

⁶ Experimental GSHP manufactured locally

⁷ Fan coil unit

3.3 Instrumentation in SEPD project

To measure GSHP system performance, sensors were installed in each of the properties. Figure 3-3 presents a typical instrumentation scheme for a property with a vertical GHE configuration. A detailed list of the instrumentation for each property is described in Appendix B. A brief description is included next.

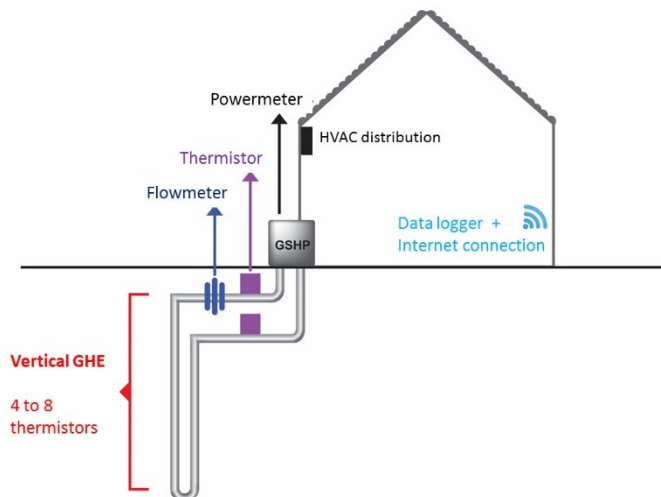


Figure 3-3: Typical instrumentation for a property with a vertical GHE installed

3.3.1 Measurement of temperature

The thermistors used in this project are negative temperature coefficient (NTC) thermistors from Emerson™. They have been calibrated by the manufacturer and verified in our laboratories, and were specified to work between -50 °C to 100 °C. For this project, most of the measurements were between 0 °C and 50 °C. A measurement error of less than 0.6 °C was indicated by the manufacturer for this temperature range measured. However, our measurements indicated that error can be as high as 5 °C as exemplified later in Section 3.4.4. The thermistor was also supplied with an extension cable and the length of this cable was predetermined before procuring the thermistors.

The thermistors are typically installed and used for the following purposes:

1. Thermistors installed along the GHE measuring ground temperature before and during system operation. Those thermistors are installed on the outside pipe wall of the GHE. The measurements prior to the commissioning of the system can provide the undisturbed ground temperature. This datum is a key design parameter required to design GSHP systems. During GSHP systems operation, these thermistors can give an indication of the ground temperature response from applying a thermal load into the GHEs.
2. Thermistors to measure outside air temperature where possible. The thermistors are typically installed at the outside wall of the building, or less ideally in the shed where the data logger is located. The latter scenario does not measure the true outside air temperature but may give some indication of the true value.
3. Thermistors installed around the GSHP that are used to monitor the temperature of the water entering and exiting the GSHP. These are key parameters required to calculate the heating (or cooling) power from the ground or to the building.

The thermistors used to measure the ground temperature along the GHE are typically attached to the pipes by using cable ties as shown in Figure 3-4 below. These thermistors are expected to measure the temperature of the ground (or grout) rather than the fluid temperature inside the pipes due to the low thermal conductivity of the high-density polyethylene (HDPE) pipe used as the GHEs. A more accurate measurement is possible if the thermistor is inserted into the pipes. However, this increases the risk for leakages, hence was not desired in this project.

Additional thermistors are installed around the GSHP to measure the fluid temperature inside the pipe. To do this, a pressure-temperature (PT) port was used (Figure 3-5a), where the thermistor is put inside a special purpose-built and waterproof enclosure (called a 'thermowell') to prevent water leakages. Alternatively, if the pipes around the GSHP are made from metal with a higher thermal conductivity than HDPE pipes (such as copper pipes), then the thermistors can be directly attached with cable ties to the pipes as shown in Figure 3-5b. Pipe insulation was added to minimise disturbance from ambient air temperature in the latter installation. It was later discovered that the ambient air temperature significantly affects the reading of the measured fluid temperature. This means that both the PT port and insulation were not sufficient. This will be further discussed in the next section as part of the experimental error.

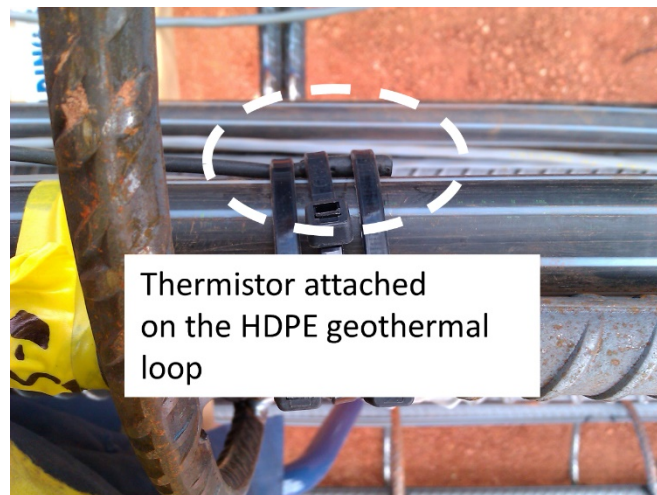


Figure 3-4: Thermistor attached on the geothermal loop

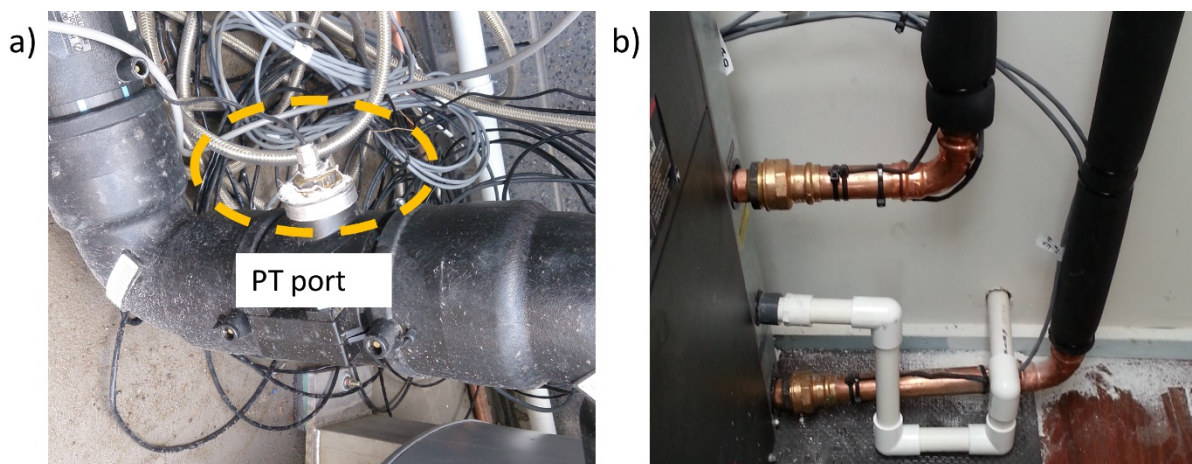


Figure 3-5: Thermistor installed in a PT port (a) and thermistor on a copper pipe (b) around a GSHP before insulation is installed

3.3.2 Measurement of flow rate

The water flow rate entering and exiting the GSHP is also one of the key parameters required to calculate the heating (or cooling) power from the ground or to the building. To do this, a multi-jet flow meter was installed as shown in Figure 3-6. The flow meter sends an analog signal to the data logger where each pulse represents 10 L. This 10 L/pulse specification of the flow meter may cause a measurement error when the water flow rate is low. Overall, the flow rate measured was between 0.4 L/s up to 2.5 L/s, with an overall error measurement observed was between 5 to 10%. Higher flow rate typically used in the larger horizontal system such as the one in Main Ridge.

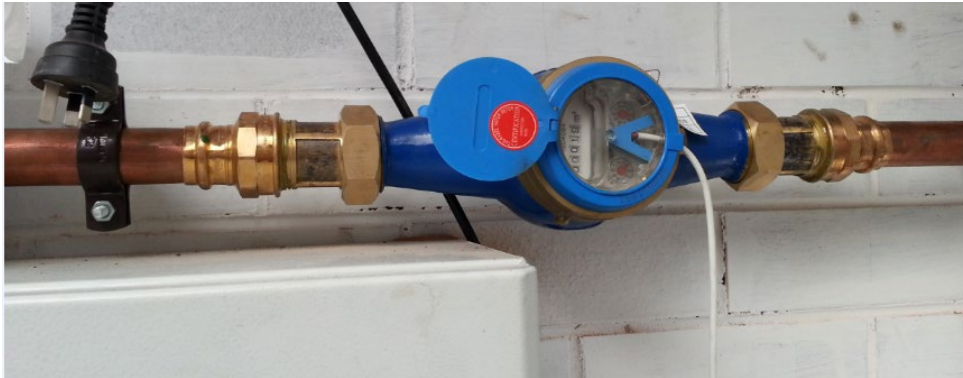


Figure 3-6: Flow meter installed in one of the monitored properties

3.3.3 Measurement of electricity consumption

An energy analyser is used to measure the amount of power consumption used to run the GSHP system. This includes both the power consumption of the heat pump and the fluid circulation pump required to run the systems. The energy analyser used is a WM22-D from Emerson™ (Figure 3-7), which is capable of measuring both single and three-phase power systems. Current transformer (CT) are used in conjunction with the analyser to measure the current drawn by the electrical circuit. In a single phase system, 2 CTs are required as shown in Figure 7-a, while in a three-phase system, 3 CTs are required as shown in Figure 3-7-a. The users of the systems are also encouraged to provide their electricity bill to be cross-referenced with these measured power consumptions.



Figure 3-7: Energy analyser and current transformers used to measure the power consumption of the GSHP system: a) for a single phase system, b) for a three phase system

3.3.4 Data recording

The sensors described above are connected to a data logger supplied by Emerson™, shown in Figure 3-8a. Three smaller data loggers from a second manufacturer (Phasefale™) was trialled with a less successful outcome in Murrindindi (Figure 3-8b). This data logger by Phasefale™ randomly stopped recording data every few days even with enough memory available. This resulted in limited and incomplete data to conduct a detailed analysis.

The standard data logger from Emerson™ has the following capabilities:

- Read and record up to 24 temperature measurements (controlled by XWEB 500D),
- Read and record up to 5 flow meters measurements (IProGenius – IPG100D),
- Read and record power consumption by using an energy analyser (WM22D),
- Programmable recording interval, where the maximum sampling frequency is 1 measurement every 15 seconds,
- Data can be stored in a text file (.txt) or in a comma-separated value (.csv) file format,
- Web interface with local and remote access capabilities, allowing real-time monitoring and analysis.

In this SEPD project, most of the data loggers were set to record data in a 5 minutes interval. With this configuration, the internal memory of the data logger is adequate to record data from all sensors up to 2.5 months. Wherever possible, this data logger is connected to the internet of the properties monitored to allow remote access to the data loggers.



Figure 3-8: Standard data logger used in the SEPD project from (a) Emerson™ and (b) Phasefale™

3.4 Performance and limitations of instrumentation equipment

This section describes some of the problems encountered during the data collection phase of the project and the steps taken to minimise them. The severities of some of the problems are rather trivial and most were easily solved by pre-processing the recorded data prior to the analysis stage. However, some problems may require a technician, such as a plumber or an electrician to replace the malfunctioned piece of equipment. Occasionally, the more severe problems can cause data loss for several weeks (even months), in which data analysis was not possible. The period when this happens is identified when the results are presented in Chapter 4.

3.4.1 Ambient air temperature influence

The ambient air temperature can affect the measured fluid temperature. This is especially crucial for those sensors around the GSHPs because this temperature determines how much thermal energy is provided by the ground. This inaccurate measurement can result in an under or overestimation of the thermal energy provided to the building.

In this SEPD project, these sensors installed around the GSHP are normally either insulated or installed inside a PT port to minimise the influence of the ambient air temperature. However, it was later discovered that this was insufficient as exemplified by Lu [47] in Figure 3-9. This figure indicates that the pipe wall temperature highly correlates with the ambient air temperature when the system was not operated. This means that either the insulation was inadequate or the ambient temperature may have an impact through the thermowell (see Figure 3-5a) since it is made of stainless steel, which conducts heat easily.

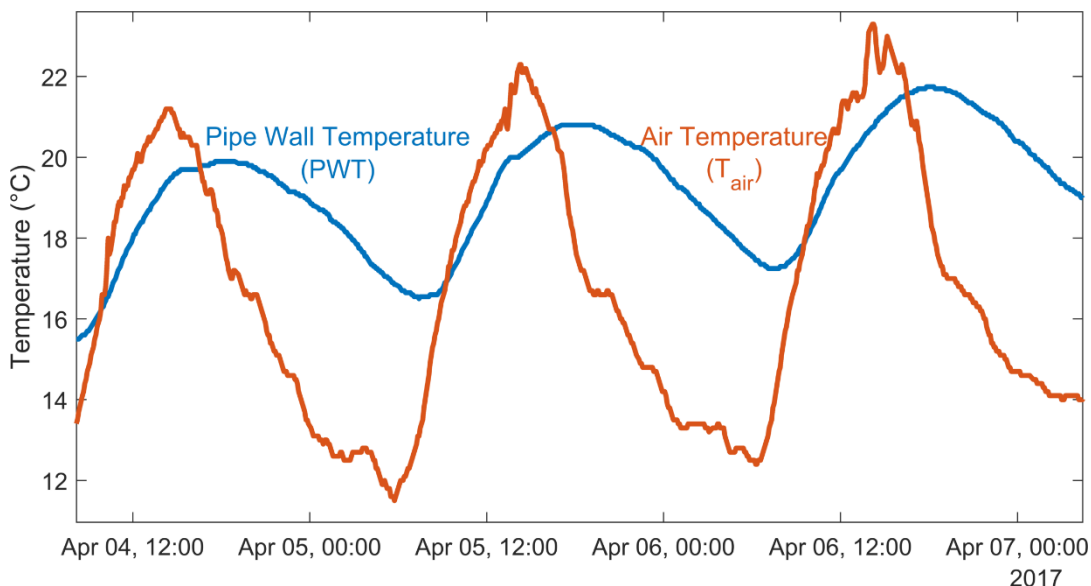


Figure 3-9: Influence of air temperature on pipe wall temperature when the system was not running (taken from [47])

The above effect is expected to be less significant when the GSHP system is in operation. The heat extraction (or rejection) process by the GSHP should have a more dominant effect in the fluid temperature rather than the effect of this ambient air temperature. Furthermore, the most relevant variable for the analysis is the *difference* in the inlet and outlet fluid temperature rather than their individual measurements. This means that even if there is some effect from the ambient temperature during operation of the system, this effect should cancel itself out once the temperature difference is calculated. Moreover, while fluid temperature affects GSHP efficiency (CoP), the difference of at most 2C when in operation renders the same CoP from a practical point of view for most GSHPs.

3.4.2 Power outage

Some of the projects are located in a remote location and being affected by a frequent power outage. This means that the data logger often lost power and unable to record data. This power outage is extremely disruptive for example, for the site in Murrindindi. The data loggers were often turned off due to power outages. This has caused limited data to be available for analysis.

Similarly, there were some occasions that the data loggers were accidentally switched off. Examples of this are when a third party unplugged the data logger from the power supply for some unknown reason or if the property owners are away on holidays. Wherever possible, they are noted and excluded from the analysis.

3.4.3 Inconsistent recording interval

The data logger does not record (or measure) all the sensors at the 'exact' same time. The data logger consists of 5 channels: three channels for temperature measurements, one for water flow rate measurements and one for power consumption measurements. All these five channels record data at a slightly different timeframe. This is best illustrated in Figure 3-10, which presents a screenshot for the data collected between 3rd and 5th September 2015 from the Main Ridge project. The recorded data for four channels of the data logger (3 devices responsible for temperature measurements and 1 device for water flow rate measurement) started on the 3rd of September at roughly 4:42 PM. Despite that, the timestamps on all four devices varied from 4:42:03 to 4:43:45. It was not clear to the author whether each device measured the data at a different timestamp or if the data was measured at the same time, but recorded/saved at a different timestamp. In this thesis, the former was assumed.

These timestamp misalignment gets worsened over time. The data logger is typically set to record at every 5 minutes interval. However, the example in Figure 3-10 indicates that the recording interval could vary between 300 to 370 seconds and gets more inconsistent over time. In Figure 3-10, it can be observed that after 536 data points recorded (roughly 48 hours period), device 4 lagged behind device 1 by more than one hour. This means that for this 48-hour period, device 4 actually recorded 549 data points, while device 1 only recorded 536 data points. It should be noted that 48 hours' worth of measurements at 5 minutes interval should be equal to (48 hours x 12 measurements/hour) 576 measurements. Hence, both devices actually recorded less data than expected.

The above limitations created some challenges during data analysis. The data collected needs to be pre-processed using some algorithm to shift the measurements to the closest 5 minutes time interval. Interpolation technique was employed to fill the gaps in the data as required. This data pre-processing was implemented in Python. The commented code is included in Appendix C.

	A	C	I	J	Q	R	S	Z	AA	AB	AD	AE
1	Device 1 - temp sensor			Device 2 - temp sensor			Device 3 - temp sensor			Device 4 - flow meter		
2	Time	Pb 1		Time	Pb 6		Time	Pb 6		Time	M1_Total	flow B
3	03/09/2015 16.42.24	11.6		03/09/2015 16.42.08	14.4		03/09/2015 16.43.45	10.8		03/09/2015 16.42.03	30206	
4	03/09/2015 16.47.33	11.6		03/09/2015 16.48.14	14.4		03/09/2015 16.48.55	10.9		03/09/2015 16.47.12	30206	0
5	03/09/2015 16.52.43	11.6		03/09/2015 16.53.24	14.4		03/09/2015 16.54.05	11		03/09/2015 16.52.22	30206	0
6	03/09/2015 16.57.52	11.6		03/09/2015 16.59.32	14.4		03/09/2015 16.59.15	11.2		03/09/2015 16.57.31	30206	0
7	03/09/2015 17.03.01	11.6		03/09/2015 17.04.41	14.4		03/09/2015 17.04.24	11.2		03/09/2015 17.02.39	30206	0
8	03/09/2015 17.09.07	11.6		03/09/2015 17.09.48	14.4		03/09/2015 17.09.31	11.2		03/09/2015 17.07.49	30206	0
9	03/09/2015 17.14.16	11.6		03/09/2015 17.15.36	14.4		03/09/2015 17.14.40	11.2		03/09/2015 17.12.56	30296	0.29316
530	05/09/2015 16.13.39	11.4		05/09/2015 16.21.25	14		05/09/2015 15.47.42	11		05/09/2015 15.01.17	5404	0.941558
531	05/09/2015 16.18.47	11.4		05/09/2015 16.26.32	14		05/09/2015 15.53.48	11		05/09/2015 15.06.23	5694	0.947712
532	05/09/2015 16.23.56	11.4		05/09/2015 16.31.40	14		05/09/2015 15.58.58	11		05/09/2015 15.11.32	5984	0.938511
533	05/09/2015 16.29.04	11.4		05/09/2015 16.37.47	14		05/09/2015 16.04.06	11		05/09/2015 15.16.41	6284	0.970874
534	05/09/2015 16.34.12	11.4		05/09/2015 16.42.55	14		05/09/2015 16.10.11	11		05/09/2015 15.21.50	6574	0.938511
535	05/09/2015 16.39.21	11.4		05/09/2015 16.48.04	14		05/09/2015 16.15.19	11		05/09/2015 15.27.01	6864	0.932476
536	05/09/2015 16.44.28	11.4		05/09/2015 16.53.51	14		05/09/2015 16.21.27	11		05/09/2015 15.32.09	7154	0.941558

Figure 3-10: Example of the inconsistent recording interval on the data recorded from Main Ridge

3.4.4 Instrumentation malfunction

Several of the instrumentation malfunctioned over the 4 years monitoring period. The most susceptible sensors were the thermistors installed underground, especially those below the groundwater table. The damage was hypothesised due to moisture ingress over time, which disturbs the temperature reading. An example of this is shown in Figure 3-11, where the thermistor measuring the ground temperature at the bottom of the GHE at Cheltenham started to malfunction after 2 years. Another example is presented in Figure 3-12, where one of the thermistors installed at Thornbury seems to record consistently lower ($\pm 5\text{ }^{\circ}\text{C}$) temperature reading than expected. Figure 3-13 presents another example where a pit in Murrindindi (containing sensors which are connected to extension cables) was waterlogged due to consecutive period of heavy rainfall. This caused most of the underground sensors in Murrindindi to malfunction. Most of these malfunctioned underground sensors were unable to be replaced as they are buried. Malfunction in the flow meter and power meter were found to be much less frequent than for the thermistors.

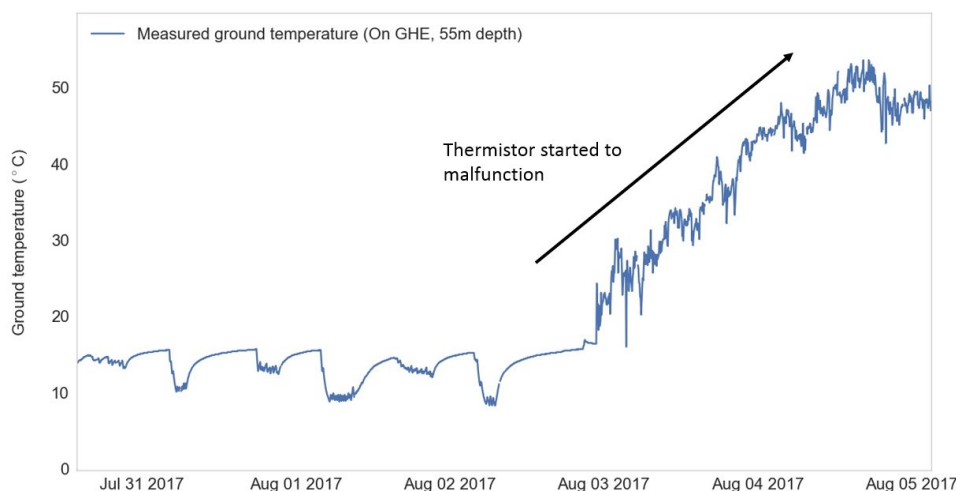


Figure 3-11: Example demonstrating that one of the thermistors at Cheltenham started to malfunction

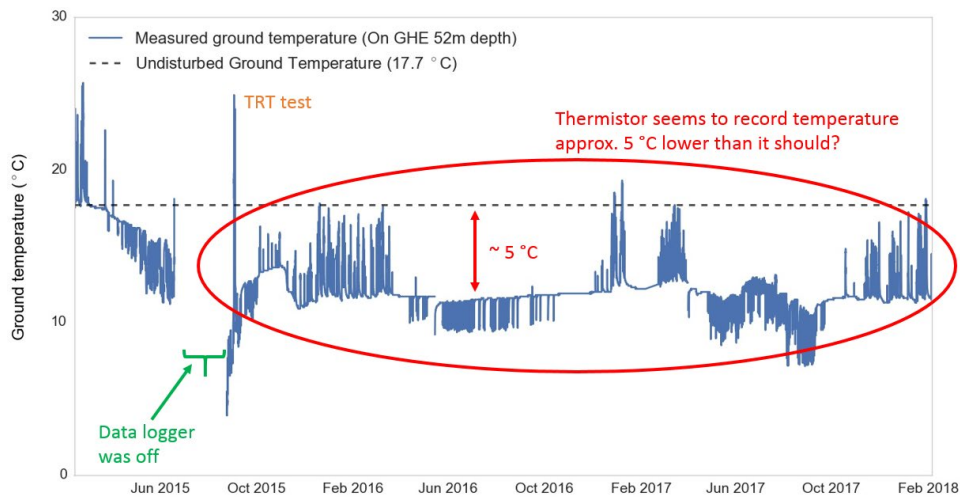


Figure 3-12: Example demonstrating that one of the thermistors at Thornbury consistently recording lower value than expected



Figure 3-13: Waterlogged pit in Murrindindi due to consecutive period of heavy rainfall

The data logger can also malfunction throughout the monitoring period. Most of the time, the data logger only needs to be restarted. However, there have been some occasions that most of the channels inside the data logger operate normally, but one channel suddenly stopped operating. Some data were lost until technicians or operators were brought on site. An example of this is the data logger at Ashburton where one of the channels malfunctioned and the data from three of the sensors were lost for the first half of 2017. This happened despite the rest of the data logger's channels had been recording as usual without any irregularities.

3.5 Analysis procedure

This section describes a typical analysis procedure undertaken in the SEPD project. The data collected are typically in a text file (.txt) or in a comma-separated value (.csv) file format. The analysis was mainly undertaken using a Python script developed by the author to computationally efficiently deal with such large datasets collected over extended periods of time and at many different sites. The commented code is included in Appendix C.

The following briefly described a typical analysis procedure undertaken at each site:

- 1) Collected raw data are first pre-processed. This is mainly to fix any irregularities in the recorded data, such as errors, anomaly readings and missing data as discussed in Section 3.4.
- 2) This pre-processed data is then merged with the master data file which contains all the collected data from that particular site
- 3) Once the most up to date master data file has been created, several key variables that describe the GSHP systems performance are calculated:
 - a. Heating (or cooling) power from the ground or to the building.
This power is given by:

$$Q = \rho_w \cdot F \cdot (T_{in} - T_{out}) \times C_w \quad (7)$$

where Q (W) is the heating (or cooling) power, ρ_w is the density of water (kg/m^3), F is the water flow rate (m^3/s), T_{in} and T_{out} ($^{\circ}\text{C}$) are the water temperatures entering and exiting the GSHP, and C_w ($\text{J/kg } ^{\circ}\text{C}$) is the volumetric specific heat capacity of water. In the analysis, it was assumed that $\rho_w = 1,000 \text{ kg/m}^3$ and $C_w = 4,200 \text{ J/kg } ^{\circ}\text{C}$

- b. The amount of heating and cooling usage hours of the systems. These are calculated based on the observed usage of the system, indicated when the GSHP is on.
- c. The amount of heating and cooling energy provided to the monitored property by using Equation (7) along with their electrical energy consumption as measured by the power meter.
- d. The annual average efficiency or seasonal performance factor (SPF) of the system.
This SPF is given by:

$$SPF = \frac{\text{Energy supplied to the building}}{\text{Energy consumed by the system}} \quad (8)$$

The results of the analysis are presented in Chapter 4, including a more in-depth discussion for two properties with the lowest and highest system usage. Individual experimental setup and a summary of data collected from each individual property is included in Appendix B.

3.6 Summary

This chapter briefly describes the locations, dominant geology formations and the experimental setup for the SEPD project. The project monitors the GSHP systems performance in 23 residential and small commercial buildings in Melbourne. The aim of this project is to provide real-life performance of the systems under Australian climatic condition since the availability of such data is still severely lacking, particularly for Australia. The instrumentations used to collect the performance data installed and limitations of this field monitoring were described in this chapter. Finally, typical GSHP system performance analysis procedure is briefly described. The analysis results and further reduction of these data are presented in the next chapter(s).

4 Usage behaviour comparison based on field measurements of ground source heat pump systems in Melbourne, Australia

4.1 Overview and structure

This chapter presents the experimental results obtained during this research. GSHP systems performance data were collected from 10 different residential properties in the greater Melbourne area. The systems were monitored for two years to capture two full heating and cooling seasons.

It was noticed that the GSHP systems in all of the monitored properties were severely underused when compared to the expected use based on a typical design method. Consequently, a more detailed analysis was conducted by comparing two properties with the highest and lowest observed GSHP systems usage. The aim was to determine whether these differences in usage behaviour lead to a significantly different performance of the system. As such, this chapter investigates the unique usage pattern by the occupants for a certain timeframe and how this impact the ground temperature development overtime, as well as the financial and environmental benefits of GSHP systems.

A paper titled “Usage behaviour comparison based on field measurements of ground source heat pump systems in Melbourne, Australia” based on this chapter is about to be submitted to the journal *Energy*. However, to maintain consistency with thesis the full text of the paper is presented here. This chapter and publication are the author’s original work. Co-author authorisation forms have been included in this submission.

4.2 Introduction

In the last few years, concerns about climate change have driven an increase in renewable technology research and development to reduce carbon emissions. One such development is in ground source heat pump (GSHP) systems, which provide efficient space heating, ventilation and air-conditioning (HVAC) to buildings using sustainable energy from the ground. A GSHP system is typically more efficient than a conventional heating and cooling system and consists of a field of ground heat exchangers (GHEs), typically vertical boreholes with ground loops, connected to a heat pump on the surface that upgrades the heat (and coolth) provided to the buildings [10-12, 19], hence the adoption of this technology can reduce electricity consumption. This is particularly important for Australia since electricity generation is the highest source of carbon emissions in the country, a situation that repeats itself around the world. Based on the national average, end users can emit 0.9 kg of CO₂ equivalent per 1 kWh of electricity consumed, which is almost double the OECD average [127]. Furthermore, the electricity price in Australia is relatively high, compared to many countries around the world [87]. Therefore, the adoption of GSHP systems over conventional HVAC systems should be an attractive option in Australia, as the higher efficiency of GSHP systems compared to conventional systems will allow end users to have lower electricity consumption and carbon emissions.

Despite these advantages, the number of GSHP systems installed in Australia is much smaller per capita than in other countries such as in the USA, Canada, China and Sweden [6] due to the relatively high capital cost required to install the systems and the limited public awareness about the technology [41, 87]. The low number of local GSHP system installations further limit the availability

of full-scale experimental performance data of this technology. To date, the only publicly available GSHP system performance data in Australia corresponds to a few commercial buildings, a school, a campus library, a house and an aquatic centre [25, 79, 84-87]. Therefore, GSHP technology is not widely known and amongst those who are aware of the technology, they are sceptical about the performance and cost of the technology under Australian climatic and cost structure conditions.

In order to redress this problem, the University of Melbourne has been undertaking a full-scale pilot direct geothermal energy demonstration project since 2012, whereby the performance data from a number of properties in greater Melbourne have been collected [11, 12, 128]. Some economic analysis arising from this project has been presented in Lu et al. [41] and recently, Aditya et al. [128] presented a performance summary from ten of the monitored properties. One of the main observations arising from this monitoring program is that the GSHP systems in these properties have much lower usage than the expected usage based on a typical design recommendation. Unlike in a commercial building, the usage pattern in a residential building is significantly more variable and highly dependent on user behaviour, including the number of occupants and whether the occupants are away or at home [129, 130].

These differences between expected and actual energy usage have been observed and investigated previously in the literature mainly for conventional HVAC systems or other energy efficiency improvement technology [131, 132], but such an investigation into GSHP systems is still lacking. Previous surveys conducted in Australia and the United States found similar findings where conventional heating and cooling systems are used less than expected [133, 134]. Others have also observed behaviour such as the pre-bound and rebound effects which can cause a discrepancy between expected and actual usage [135-137]. The pre-bound effect is when the actual energy saving caused by a home improvement technology turns out to be less than the estimated potential due to an overestimation in the estimated initial energy usage [137]. The rebound effect is an increase in net energy consumption because the users take advantage of the new energy saving technology and end up using the system more [136].

These two effects along with the fact that an energy efficient technology typically requires high capital cost investment often result in lower than expected financial savings and high payback periods once this energy efficient technology is installed. This could be the case for GSHP systems, where there is little measured performance data. One previous study was conducted by analysing a survey from 78 domestic heat pump users in the UK. It was reported that higher system efficiency was observed for users who know how to operate their systems better [138]. Moreover, the impacts from user behaviour on the heat source/sink on the ground have not been analysed or reported to date. For these reasons, it is important to acknowledge the potential role of user behaviour on the design, efficiency and economics of GSHP systems, especially on residential buildings. Different user behaviour can result in different GSHP system efficiency. This can affect the economics of GSHP systems especially if it is considered as a home improvement project. The GSHP system monitoring project presented in this work offers a unique opportunity to study the potential impact of this user behaviour, where the occupants can use their GSHP systems as much or as little as they need to reflect their regular heating and cooling energy consumption. This sort of analysis is lacking in the literature.

This chapter presents a detailed GSHP system performance analysis from two residential properties located in Melbourne. These properties were selected on the basis of their usage patterns which reflected one of the highest and one of the lowest heating and cooling energy consumptions of the properties monitored. First, the distinct usage pattern between the two properties is compared. Based on these usage patterns, then the ground thermal response is discussed along with the

efficiency of the systems. Finally, the potential implication on these usage patterns on the financial and environmental viability of GSHP systems is discussed. The results from this chapter may offer insights for designers to improve GSHP system design for Australian temperate climatic condition or other countries with a similar climatic condition. Furthermore, this monitored data may give more information for homeowners, building developers and policy makers to develop more informed decisions regarding GSHP technology in Australia.

4.3 Overall project description

Ten GSHP systems were installed in greater Melbourne as part of a Sustainable Energy Pilot Demonstration (SEPD) program between 2012 and 2017. The project was started to address the lack of knowledge regarding GSHP system technology in Australia and specifically, to provide full-scale experimental data on GSHP system performance in typical residential properties. At the start of the project, there was a significant lack of full-scale experimental data on these systems available worldwide. The location of the monitored properties is shown in Figure 4-1. They were chosen to cover all the common geologies typically found in Melbourne. The conditioned floor area, along with whether the building is retrofitted or newly built, the geology, the number, orientation and total length of GHEs, the capacity of the GSHPs and details of the distribution systems installed in these properties, are summarized in Table 4-1.

The design of the GSHP systems were conducted as a joint effort by the University of Melbourne's team and our project partners. Various local installers helped with the drilling, piping installation, GSHP and HVAC system installation as well as the commissioning of the GSHP systems.

Several sensors were installed in each of the properties to measure GSHP system performance. The instrumentation consists of thermistors to measure the ground temperature along the ground loop, thermistors and flow meters to measure the temperatures and flow rate of the water flowing in and out of the GSHP on the ground side (and the building side when applicable in water to water systems), and a power meter to measure the electrical power consumption of the GSHPs, circulation pumps and fans required to run the system. All the monitoring data at each property is collected through a data logger, which can be accessed remotely for data transmission through the internet. Most of data collection in this project started in 2015 and most of the data presented in this work cover at least 2 years of monitoring period.



Figure 4-1: Location of the ten monitored properties with GSHP systems

Table 4-1: Summary of site conditions and GSHP installations at the monitored properties

Property location (refer to Figure 4-1)	Conditioned floor area (m ²)	Retrofitted (R) or newly built (NB)	Geology ¹	Number, orientation ² and total GHE length (m)	GSHP ^{3, 4, 5} heating/cooling capacity (kW)	Distribution systems
Ashburton	300	NB	Siltstone & minor sandstone	4, V, 360	³ 32/28	Floor hydronic heating, FCU ⁶ for cooling, water & pool heating
Buninyong	150	R	Deep marine deposits & sandstone	4, H, 160	³ 58/8	FCU for heating and cooling
Cheltenham	100	R	Sands with minor clay	2, V, 110	⁴ 6/9	Ducted heating and cooling
East Brunswick	50	R	Basalt	2, V, 130	³ 58/8	FCU for heating and cooling
East Melbourne	60	NB	Basalt	2, V, 120	³ 11/9	Ducted heating and cooling, water & spa heating
Footscray	100	R	Basalt	2, V, 110	⁴ 8/10	Ducted heating and cooling
Inverloch	200	NB	Siltstone & sandstone	6, V, 300	³ 18/17	Floor hydronic heating and cooling & hot water
Kangaroo Ground	400	NB	Siltstone	9, S, 320	³ 16/15	Floor hydronic heating and FCU for cooling
Main Ridge	280	NB	Basalt	8, S, 320	³ 22/17	Floor hydronic heating and hot water
Thornbury	50	R	Siltstone & minor sandstone	2, V, 100	^{3,5} 6/6	FCU for heating and cooling

¹ Based on the Geological Map of Melbourne from Energy and Earth Resources [125]

² V = vertical GHEs, H = horizontal GHEs (straight pipe), S = horizontal GHEs (slinky)

³ Water to water GSHP

⁴ Water to air GSHP

⁵ Experimental GSHP manufactured locally

⁶ Fan coil unit

4.4 Data analysis results and discussions

4.4.1 Summary of GSHP systems performance in all 10 properties

A summary of the performance data for all monitored properties is shown in Table 4-2. It can be observed here that all of the properties are heating dominant, which matches the expected thermal requirements for residential buildings in Melbourne's temperate climate. Most of the properties have run fractions between 10 to 20%, where a run fraction indicates the amount of time that the GSHP is used, in this case 10% to 20% of the year. These are significantly lower than the usage suggested by a typical design method, such as the IGSHPA's bin method. In this method, the outside air temperature is grouped into a certain bin/ frequency (usually every 2-3 °C) and assumed that heating and cooling are needed all year around [10]. The total heating and cooling required are calculated by multiplying the number of hours at each bin by the required heating and cooling needed corresponding for each bin. Based on this method, a residential house in Melbourne is expected to require heating and cooling for around 82% of the year.

This finding of significantly lower heating and cooling usage compared to the design method recommendation is in line with a previous Australian survey by Daniel et al. [133], where it was found that residents use their conventional heating and cooling systems for only part of the year and only in the living area. This causes less overall usage compared to the typically assumed all year round usage and for all parts of the house. Furthermore, the temperate climate in Melbourne is mild enough that residents can turn off their heating and cooling systems for a significant part of the year, particularly during the shoulder periods of autumn (approximately March – May) and spring (approximately September to November). This is different to many other parts of the world where heating or cooling is needed for most if not the whole year.

The low usage pattern observed here is investigated in greater detail by comparing GSHP system usage patterns between two selected properties. These two properties are located at Ashburton and Cheltenham, around 15 km apart. Due to their close proximity, it would be reasonable to expect that they are subjected to a similar air temperature distributions throughout the monitoring period and therefore, have similar annual heating and cooling requirements based on temperature differences only. These properties have been selected for this chapter because, as will be discussed later, they have significantly different usage patterns. As shown in Table 4-3 the property at Cheltenham is one of the properties with the lowest system usage (6% of the year). In contrast, the property at Ashburton is the one with the highest usage (36% of the year). The site conditions and details of the GSHP systems installed at these two properties are summarised in Table 4-3. It is important to recognise that the GSHP installed at Ashburton (32 kW) is larger than at Cheltenham (9 kW). The larger capacity used at Ashburton due to the GSHP is used to heat and cool the entire house, in comparison to the one at Cheltenham which is used only for the shared living space. This is indicated in Table 4-3 where the conditioned floor area in Ashburton is three times larger than the one at Cheltenham.

For a more detailed comparison, extended data up until August 2018 is used to capture three full season cycles of heating and cooling.

Table 4-2: Summary of GSHP system performance at the monitored properties up to January 2018

Properties location (refer to Fig. 2)	Monitored period	Total usage (hours)		Run time fraction (%) ⁸	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF ⁹	CoP ¹⁰
		Heating	Cooling		Heating	Cooling			
Ashburton	² Jun '15 – Jan '18	4,568	2,967	36	80,508	16,495	26,339	3.7	4.6
Buninyong ¹	Nov '16 – Jan '18	757	288	10	4,900	1,495	2,330	2.7	2.9
Cheltenham	Aug '15 – Jan '18	1,186	145	6	6,208	928	1,978	3.6	4.1
East Brunswick ¹	³ Aug '15 – Jan '18	177	-	-	538	-	294	1.8	2.3
East Melbourne	⁴ Jun '15 – Jan '18	2,232	1,512	17	12,414	4,593	6,216	2.7	3.3
Footscray	⁵ Jun '15 – Jan '18	2,147	407	12	12,022	1,861	5,687	2.4	2.7
Inverloch	Jan '16 – Jan '18	2,548	594	17	27,038	6,328	9,763	3.4	3.8
Kangaroo Ground	Sep'16 – Nov '17	720	302	10	5,590	3,033	1,905	4.5	4.9
Main Ridge	⁶ Sep '15 – Jan '18	1,013	-	5	16,747	-	4,736	3.5	4.0
Thornbury ¹	⁷ May '15 – Jan '18	1,245	858	9	2,925	960	2,412	1.6	2.0

¹ Properties with an experimental GSHP manufactured locally. GSHPs at East Brunswick and Thornbury were the first iteration, which may explain lower SPF than at Buninyong

² Excluding February 2017 – July 2017 when the data logger malfunctioned

³ GSHP often malfunctions, thus indicating minimal usage hours. For this reason, run time fraction was not calculated as it is not representative

⁴ Excluding December 2017 when data logger was off

⁵ Excluding January 2017 – February 2017 when flow meter malfunctioned

⁶ Excluding July 2017 – September 2017 when data was not collected. This house is a holiday house and not the main place of residence, hence the low usage hours of the system. GSHP system was also designed for heating mode only

⁷ Excluding June 2015 to August 2015 when data logger was off

⁸ Run time fractions are adjusted to exclude periods when analysis could not be performed due to data collection problems (actual usage may be more than the stated run time fraction)

⁹ Seasonal performance factor (SPF) = total energy provided to the building / total electrical energy used. The power consumption including GSHP, circulation pumps and fans

¹⁰ Estimated CoP of the GSHP (without the circulation pumps and fans power consumption)

Table 4-3: Summary of site conditions and GSHP systems installed at Ashburton and Cheltenham

Categories	Parameter	Ashburton	Cheltenham
Building description	Purpose	Residential	Residential
	Type	Newly built	Retrofit
	Conditioned floor area (m ²)	300	100
	Distribution system	Floor hydronic heating, fan coil unit for cooling, water and pool heating	¹ Ducted heating and cooling
Ground properties	Geology	Siltstone and minor sandstone	Sands with minor clay
	Undisturbed ground temperature (°C)	(was not measured) Estimated as 17.4 based on average entering water temperature to the GSHP	18.1
	Ground thermal conductivity (W/m.K)	(was not measured)	Measured through thermal response test, 1.62 [93]
Borehole characteristics	Number of boreholes	4	2
	Borehole diameter (mm)	114	114
	Borehole length (m)	90	55
	U-loop type	Single U-loop	Double U-loop
	Pipe outer diameter (mm)	32	32
	Borehole spacing (m)	Varied, 9 to 13	8.7
	Grout type	Cement-based grout, mixed on site. 100 kg sand, 100 kg cement, 20 g bentonite, 55 L water	Bentonite grout with silica sand. Note slightly different mix between 2 boreholes
	Grout thermal conductivity (W/m.K)	2 (measured by using a KD2 needle probe by Decagon)	1.1 to 1.3 (measured by using a KD2 needle probe by Decagon)
GSHP characteristics	GSHP type	Water to water	Water to air
	Number of GSHPs	1	1
	GSHP heating capacity (kW)	32	6
	GSHP cooling capacity (kW)	28	9
Instrumentation	Thermistors	14 thermistors in 2 GHEs	8 thermistors in 2 GHEs
	Thermistors	4 thermistors around GSHP	2 thermistors around GSHP
	Flow meter	2 flow meters around GSHP	1 flow meter around GSHP
	Power meter	In GSHP	In GSHP
	Monitoring period	Since June 2015	Since August 2015

¹Hot water heating at Cheltenham is not heated by the geothermal system, hence this is excluded.

4.4.2 Annual heating and cooling usage

A summary of the annual performance data at these two properties is shown in Table 4-4 below. There was no data collected from the property at Ashburton between February and July 2017 due to a data logger malfunction which for various reasons, could not be remedied immediately.

The usage hours in both properties suggest that they are both heating dominant. The heating usage at Ashburton in 2017 seems to be lower than the cooling usage because data was lost during a significant part of the heating season (in Australia, heating season occurs mid-year). The heating usage hours at Ashburton in 2018 is lower compared to the first two years of operation. The occupier explained that during the winter in 2018, they turned off the heating for the pool as they found out that they were not using the pool as much as in previous years.

In 2018, the overall heating and cooling usage at Cheltenham significantly increased compared to the previous years. Earlier, the usage of the system was around 6% of the year, which increased to 12% in 2018. One potential explanation is that the occupier had a solar PV system installed in that year. Prior to 2018, the heating system was turned off in the morning because the house naturally heated up as the day progressed. However, since the solar PV system was installed, the occupier took advantage of the electrical energy generated by the system to heat the house faster. This is somewhat related to the rebound effect, where the new solar PV system incentivised the occupier to use the GSHP system more than in previous years.

The overall usage of the system at Ashburton (34 to 45 % of the year) is significantly more than the overall usage at Cheltenham (6 to 12% of the year). Despite this, it can be assumed that both houses were subjected to similar weather conditions given their proximity. One possible explanation is that the GSHP system at Ashburton is also used to provide domestic hot water and pool heating, which contributes to the higher overall usage of the system.

A second possible explanation is the distinct user behaviour in these two properties. The occupier at Ashburton set automatic set points to maintain comfortable indoor air temperature at all times, whereas the occupier at Cheltenham only turned the system on as required. Furthermore, as confirmed by the occupiers at each property, the set points of the system at Ashburton were 20 and 22 °C for heating and cooling respectively, whereas the one at Cheltenham were 19 and 25 °C for heating and cooling respectively. Wider set point temperatures should result in a system being used less throughout the year. Design guidelines such as ASHRAE [139] suggest that a comfortable indoor temperature is between 20 to 24 °C depending on the humidity. Compared to this design recommendation, the set points used by the occupier at Ashburton is well within this range, whereas the set points at Cheltenham are slightly outside this range. These factors may partly explain why the system at Ashburton has been used more often. These usage hours directly correlate with how much energy is provided to the building and the amount of electricity consumed by the GSHP systems.

Table 4-4: Yearly summary of GSHP systems performance at Ashburton and Cheltenham

Properties location	Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF ³	CoP ⁴
		Heating	Cooling		Heating	Cooling			
Ashburton	Jun – Dec 2015	1,138	371	34	17,794	2,276	5,277	3.8	4.7
	Jan – Dec 2016	2,631	1,286	45	48,378	6,838	14,840	3.7	4.5
	¹ Jan – Dec 2017	755	1,059	² 45	13,638	6,005	5,535	3.5	4.6
	Jan – Aug 2018	813	1,321	36	13,503	6,877	6,098	3.3	4.4
Cheltenham	Aug – Dec 2015	183	32	6	1,110	208	327	4.0	4.5
	Jan – Dec 2016	481	44	6	2,471	278	780	3.5	4.0
	Jan – Dec 2017	522	64	7	2,627	409	863	3.5	4.0
	Jan – Aug 2018	630	56	12	3,061	363	1,014	3.4	3.8

¹ Excluding February 2017 – July 2017 when the data logger malfunctioned

² Run time fractions are adjusted to exclude periods when analysis could not be performed due to data collection problems (actual usage may be more than the stated run time fraction)

³ Seasonal performance factor (SPF) = total energy provided to the building / total electrical energy used. The power consumption including GSHP, circulation pumps and fans

⁴ Estimated Coefficient of performance (CoP) of the GSHP (without the circulation pumps and fans power consumption).

The seasonal performance factor (SPF) is an indication of efficiency and is calculated based on the amount of energy provided to the building and total electrical energy required by the system. The SPF for both properties in a given year are similar. However, these SPFs decreased over the monitoring period. One potential explanation for this decrease in SPF is that most of the usage of the systems at both properties are for heating. This means that the available thermal energy in the ground might be over-extracted (more energy extracted during winter than injected during summer) leading to a decrease in efficiency over time.

It should be noted that a significant part of the data for Ashburton in 2017 was not included due to a datalogger malfunction, which may increase or decrease the actual SPF compared to the one reported here. Similarly, the full data for 2015 and 2018 were not available due to the timing of the project and when the analysis was conducted, which may affect the actual average SPF in 2015 and 2018. The coefficient of performance (CoP) of the GSHP is estimated based on the estimated power consumption of the fans and circulation pumps used to circulate water or air in the ground heat exchangers or distribution systems. Even though both properties have similar SPF, the estimated GSHP's CoP at Ashburton is significantly higher than at Cheltenham. The reason that the high GSHP's CoP of Ashburton was reduced to an SPF similar to that recorded for Cheltenham may be at least partly due to the relatively higher electricity consumption required to run the larger circulation pumps at Ashburton. This circulation pump requires larger electricity since it needs to supply a larger quantity of water due to the larger and more complicated system (32 kW). If only the heat pump is considered, the GSHP unit at Ashburton is more efficient than at Cheltenham.

4.4.3 Monthly heating and cooling usage

In this section, the monthly heating and cooling usage in both properties are examined and discussed. Figure 4-2 presents the normalised heating and cooling energy provided to both properties. The figure is normalised to the highest accumulated monthly heating or cooling energy provided to each building in each year. A normalised energy of 1 means the highest energy provided to the building occurs at that month. This normalisation was conducted to allow usage pattern comparison between both properties as they have different installed GSHP system capacities.

The highest cooling energy delivered to the building typically occurs in the middle of the summer (at the start or at the end of the year in the southern hemisphere) and the highest heating energy typically occurs in the middle of winter (mid-year). Another observation from Figure 4-2 is that the heating and cooling usage at Ashburton is consistent all year round, whereas the heating and cooling usage at Cheltenham significantly dropped off at shoulder season (March, April, October and November), except on November 2017. In fact, the system at Cheltenham was not used at all in November 2015 and March 2018, even though the occupiers were present and were not away on holiday.

In terms of the heating and cooling usage mix, the property at Cheltenham typically uses either heating or cooling depending on the season. In contrast, some heating usage can be observed at Ashburton even during summer months. This minor heating usage was probably due to pool heating or hot water generation which should occur consistently throughout the year.

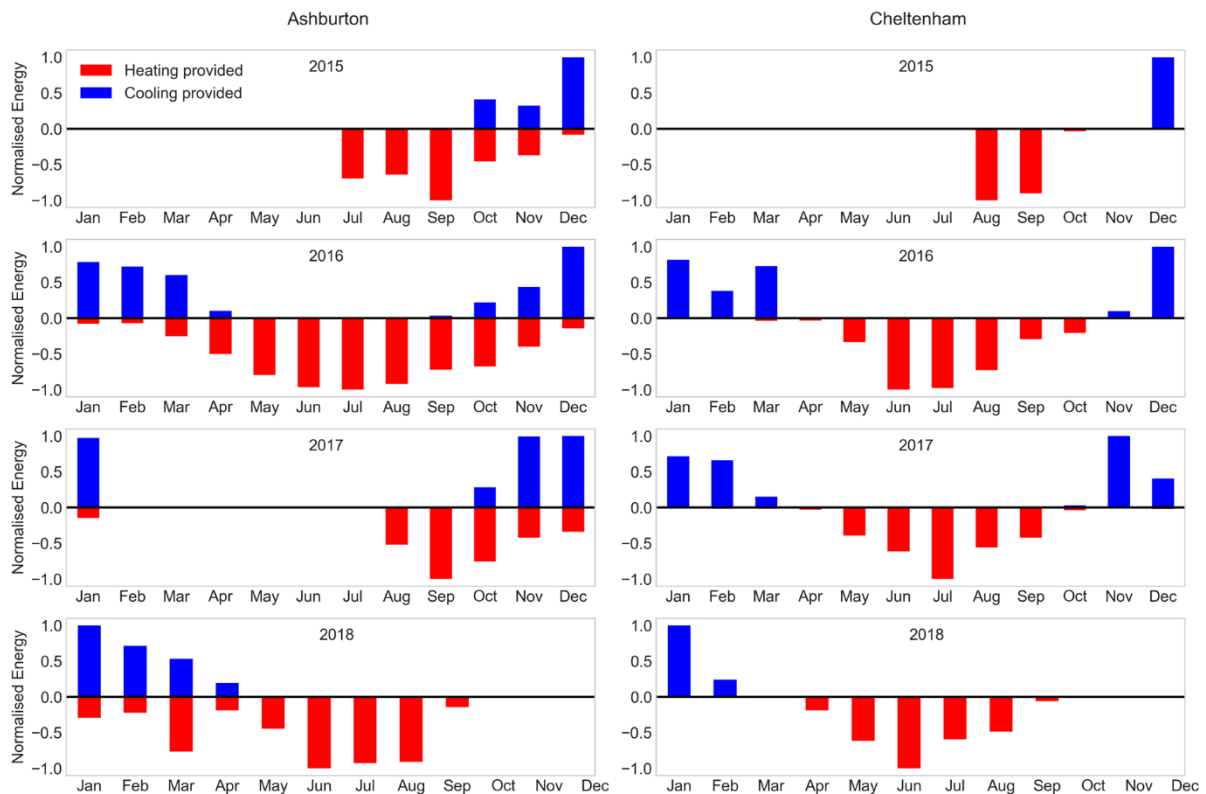


Figure 4-2: Normalised monthly heating and cooling provided for each property in kWh

4.4.4 Daily heating and cooling usage

The daily thermal usage in each property is investigated next. The total energy provided to the building each day can provide a reflection of how much the system is used and the overall proportion between heating and cooling usage.

Figure 4-3 presents the daily thermal energy provided to the building at Ashburton. This house requires a maximum of around 100-250 kWh daily heating energy and 100-150 kWh daily cooling energy. For a 30 kW system, this total daily usage translates to around 8 and 5 hours of heating and cooling at an equivalent full load capacity. This suggests that for around two-thirds of the day, the system does not operate at the full capacity. The average daily heating energy in this property is higher than the cooling energy as there is additional demand for pool and hot water heating. It can also be observed that the frequency of heating usage decreases in 2018, which confirmed the report from the occupier that they started to heat the pool less compared to the previous years.

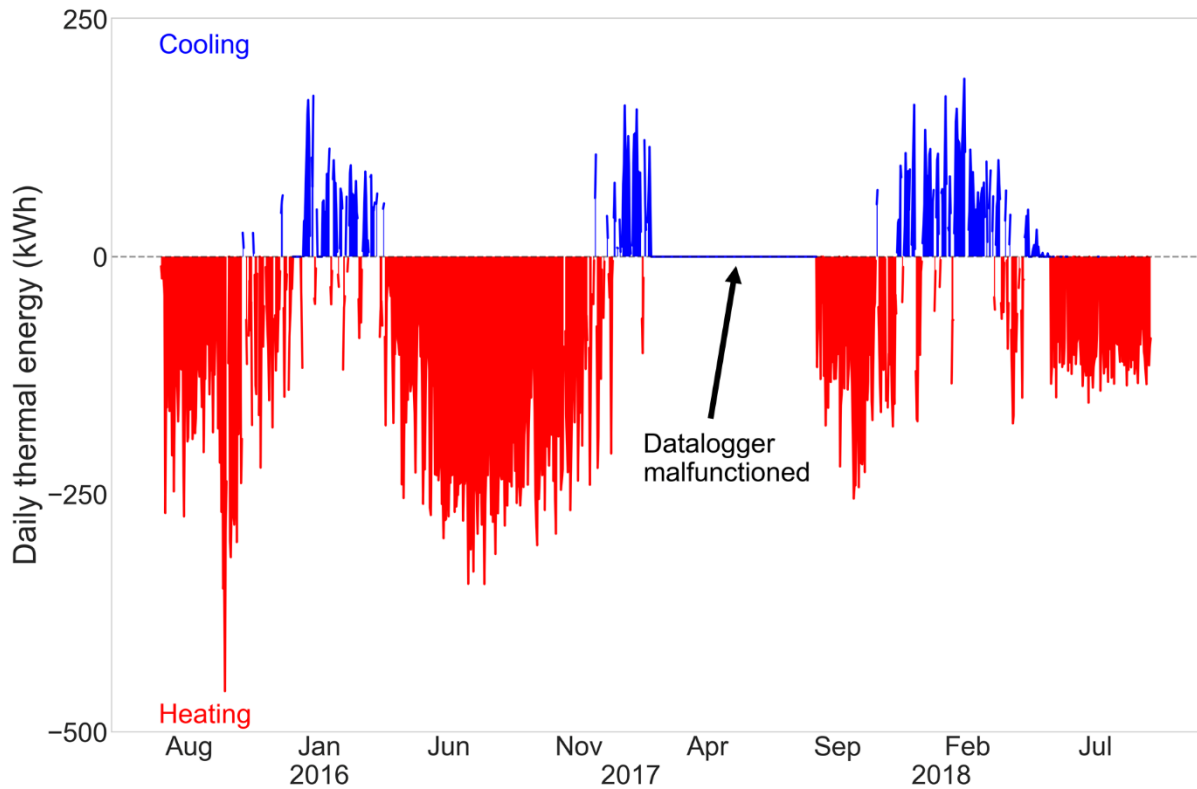


Figure 4-3: Daily thermal energy provided to the building at Ashburton in kWh

A similar observation can be made for the property at Cheltenham as shown in Figure 4-4. This property is heating dominant, where most of the daily heating usage is between a maximum of about 20 and 50 kWh while the cooling usage is between 10 and 30 kWh. This property has a smaller 9 kW GSHP system, which means that the daily thermal demand is equivalent to 6 and 3 hours of heating and cooling usage at peak load capacity. Compared to the daily usage at Ashburton, the daily usage at Cheltenham suggests that there are several periods during shoulder seasons when the systems were not used for several consecutive days. The most notable periods are during November 2015 and March 2018 where, as shown in Figure 4-4, the systems were not used at all. Finally, the usage during summer at this property is rather minimal with a total of only 200 hours or 1,300 kWh for 3 cooling seasons. The occupier confirmed that they tend to run ceiling fans during summer months rather than using the air conditioning system. Unfortunately, the usage and energy consumption of this fan is not part of the monitoring program.

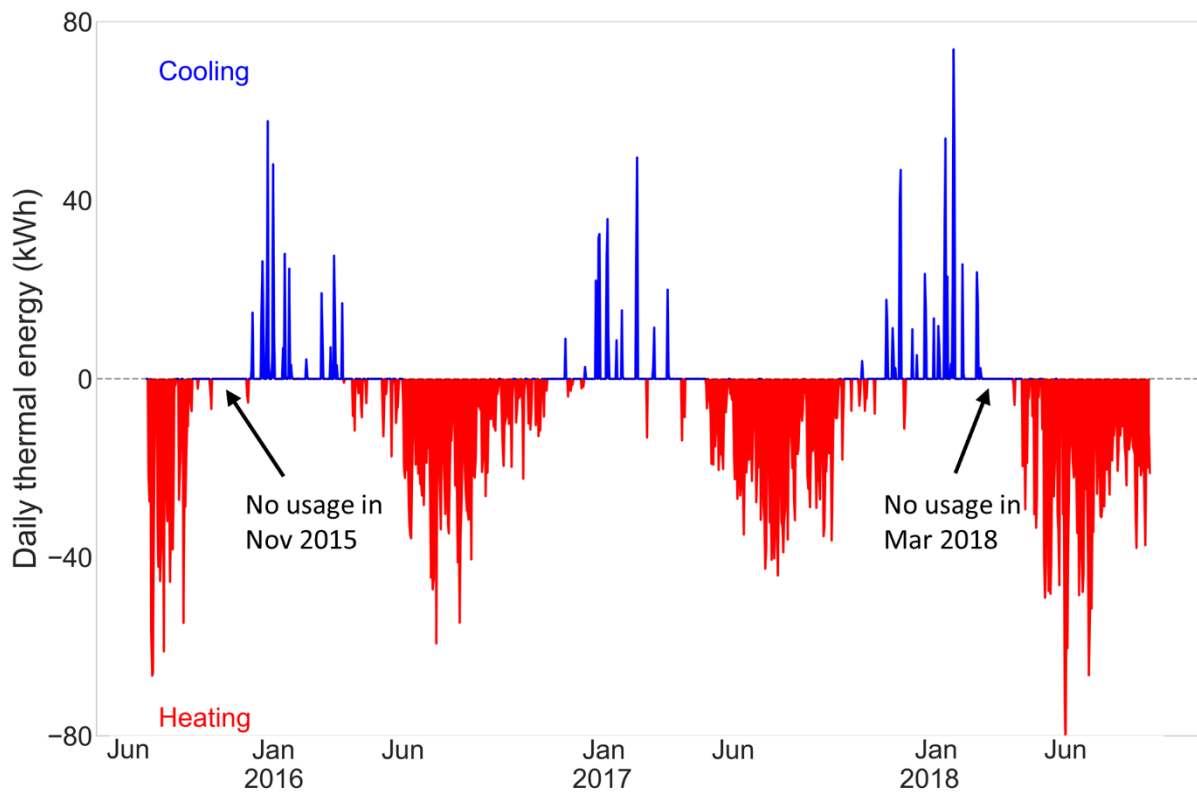


Figure 4-4: Daily thermal energy provided to the building at Cheltenham in kWh

4.4.5 Hourly heating and cooling usage

In this section, the hourly usage patterns of both properties are examined. This offers a unique and interesting insight on how the two occupiers use their respective systems with respect to the time of the day and the season. The hourly normalised heating and cooling energy for each hour in each month were averaged and presented in Figure 4-5. The energy is then normalised to the highest average energy provided to the building for each hour of the month, where a normalised energy of 1 means that this hour has the highest average energy usage for that month. As before, this normalisation is conducted to allow comparison between both properties as they have different GSHP capacities.

Similar to previous observations, the usage at Ashburton is more consistent throughout the year, while the majority of the usage at Cheltenham is from May to September during the heating season. For both properties, the highest average thermal energy demand occurs in the early morning during winter.

However, what is clear is that the two properties display quite distinctive pattern of use. For most of the year, the system at Ashburton has heating usage throughout the night. During the day, the house either has low heating usage during winter or some cooling usage during summer. The thermal energy provided to the building typically increases rapidly around 6 pm in the evening, runs throughout the night, then decreases from around 7 am in the morning. This usage pattern is similar to what would be expected for occupants with full-time work (and children with full-time school) where the house is empty from approximately 8 am to 6 pm.

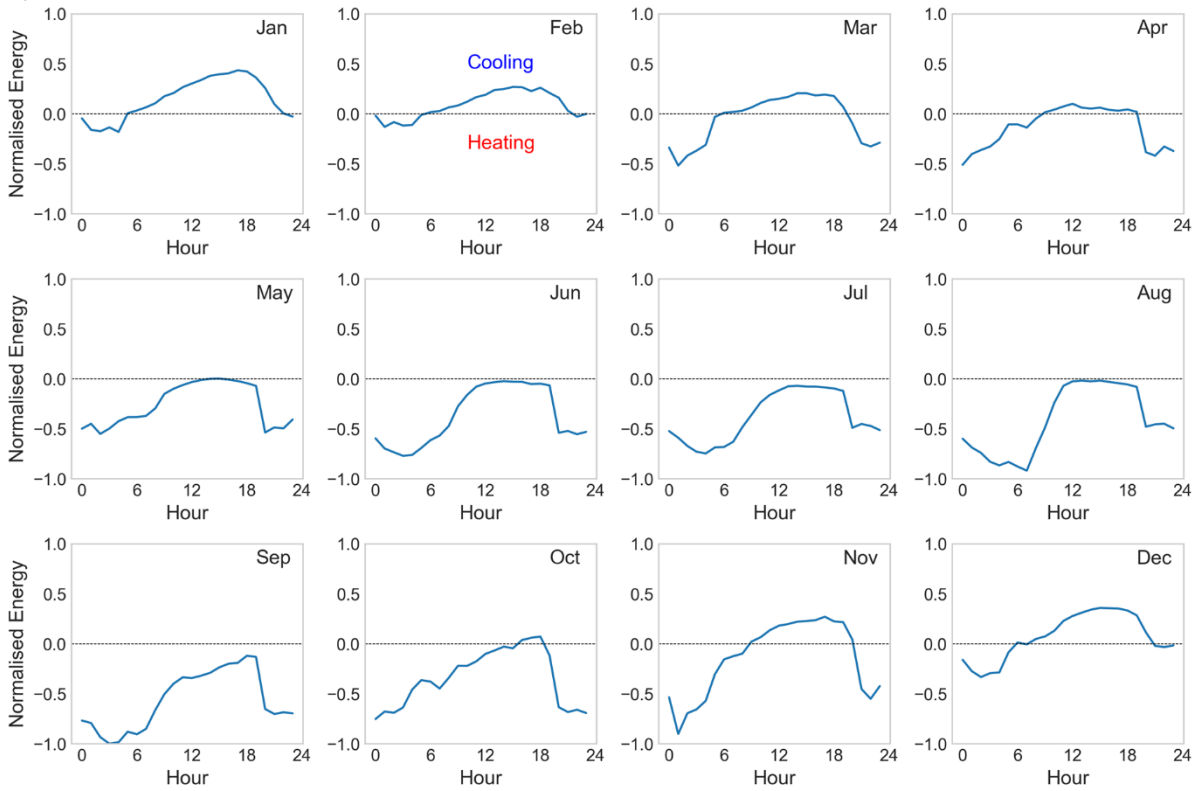
In contrast, the property at Cheltenham indicates a usage pattern more typical of at least one occupant who stays at home during the day. This particular occupier switches off the system during the night and turns it back on especially during the winter season at around 5 am in the morning to preheat the house before the day starts. The heating usage then typically decreases around mid-day as the house warms up and the outside air temperature rises. At this time, the indoor temperature has reached a comfortable temperature range without the need for any additional space heating or cooling. The heating demand typically has a sharp increase in the evening around 6 pm as the outdoor temperature drops and usually turned off closer to midnight. The cooling need at this house during the summer typically increases as the day progresses and decreases towards the evening, which correlates with the outside air temperature.

These hourly usage patterns may reflect on how the occupants use their heating and cooling systems according to their presence. For example, during a winter night, the occupiers have two (extreme) choices, either they run the heating system overnight or they can turn it off. Similarly, during the day, occupiers can be present at home and they may use their heating system or they can be away, and in this case, the heating system may be switched off. The demographic of the occupiers may also determine their energy usage pattern. Full-time workers will be away from home the longest, whereas someone who works part-time will only be away for half of the day. Furthermore, a full-time worker with children may have their heating system switched on earlier in the afternoon when the children return home from school. Other factors such as air-conditioning zoning system, pool and hot water heating can also contribute to the heating and cooling requirements of a building.

The observed data presented in Figure 4-5 suggest that the occupiers at Ashburton may follow these usage patterns: the occupiers seem to be away during the day with minimum run time, but indicate that the heating system is switched on overnight, which represent a significant energy consumption at this property. The heating demand is consistent throughout the year, indicating the usage for pool and hot water heating. Overall, these usage patterns reflect occupiers with relatively high energy demand. In contrast, the property at Cheltenham seems to be occupied throughout the day, but with minimum energy demand, except during early morning in winter months. Some of the electricity used to run the GSHP during winter days may even be offset with electricity generated by the PV system. The Cheltenham occupiers also tend to switch off the heating and cooling system throughout the night, resulting in a large energy saving. The low GSHP system usage at this property appears to represent the energy use patterns from occupiers who are energy conscious.

Despite these contrasting user behaviours, it is interesting to note that for each year, the SPF of the two systems are approximately the same (see Table 4-4 earlier). However, these differences may have some impacts beyond the efficiency of the systems. One example of this is on the ground temperature response when a thermal load is applied. Another example is the impact on the financial returns for the occupiers. These two potential impacts will be discussed in the next two sections.

a) At Ashburton



b) At Cheltenham

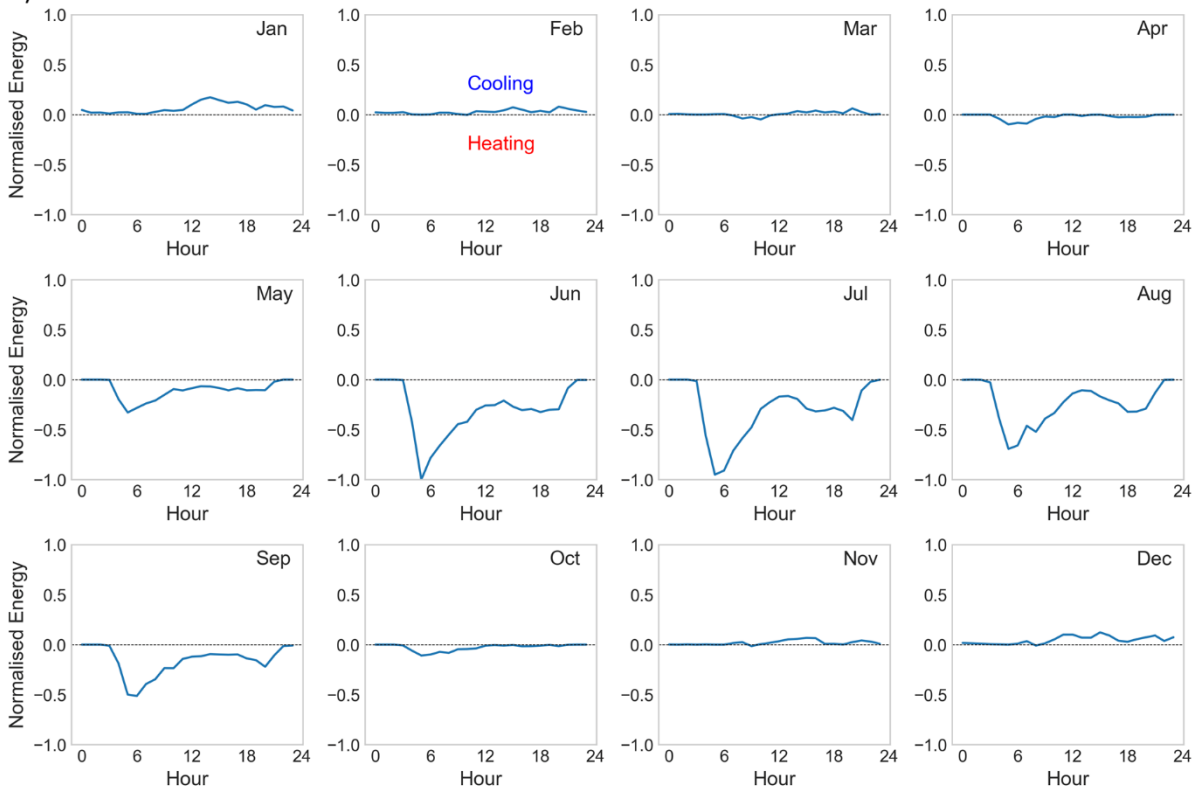


Figure 4-5: Hourly usage pattern at a) Ashburton and b) Cheltenham for each month

4.4.6 Ground thermal response

Beyond the efficiency measurement of the GSHP systems, designers and engineers are often interested in the ground thermal response of the systems after a thermal load is applied. Typically, designers of GSHP systems aim to minimise ground temperature change from year to year as the efficiency of the system highly correlates with the ground temperature. The efficiency of the system may decrease over time if the ground temperature changes too much from its initial undisturbed condition.

For this reason, several sensors were installed along the GHEs of this project. These sensors measure the temperature along the GHEs inside the grouted boreholes. The measured temperature should represent the temperature of the water at the location of the sensor during the operation of the system or, when the system is not operating, this measured temperature may represent the undisturbed ground temperature, which is the farfield ground temperature a significant distance away from the borehole which is not affected by the operation of the GSHP system.

The daily average temperature measurements from thermistors at the bottom of the GHE at Ashburton (90 m deep) and at Cheltenham (55 m deep) are shown in Figure 4-6. The undisturbed ground temperature was also measured before commissioning at Cheltenham as 18.1 °C. Unfortunately, the system at Ashburton was commissioned before the monitoring system was fully installed, hence the undisturbed ground temperature was not measured directly. However, based on significant experience in the Melbourne area and with siltstone in particular, it is likely that the mean undisturbed ground temperature along the 90 m borehole would have been about 17.4 °C. This is also supported by the method presented in Gehlin and Nordell [140], where the undisturbed temperature can be estimated based on the observed entering water temperature during the purging stage of the thermal response test. The spike in the record of about 40 °C at Cheltenham in late April 2017 was caused by a thermal response test conducted where a constant heating load was applied to the ground for 3 days. The ground measurement at Cheltenham is shown only up to August 2017 as the sensor malfunctioned thereafter.

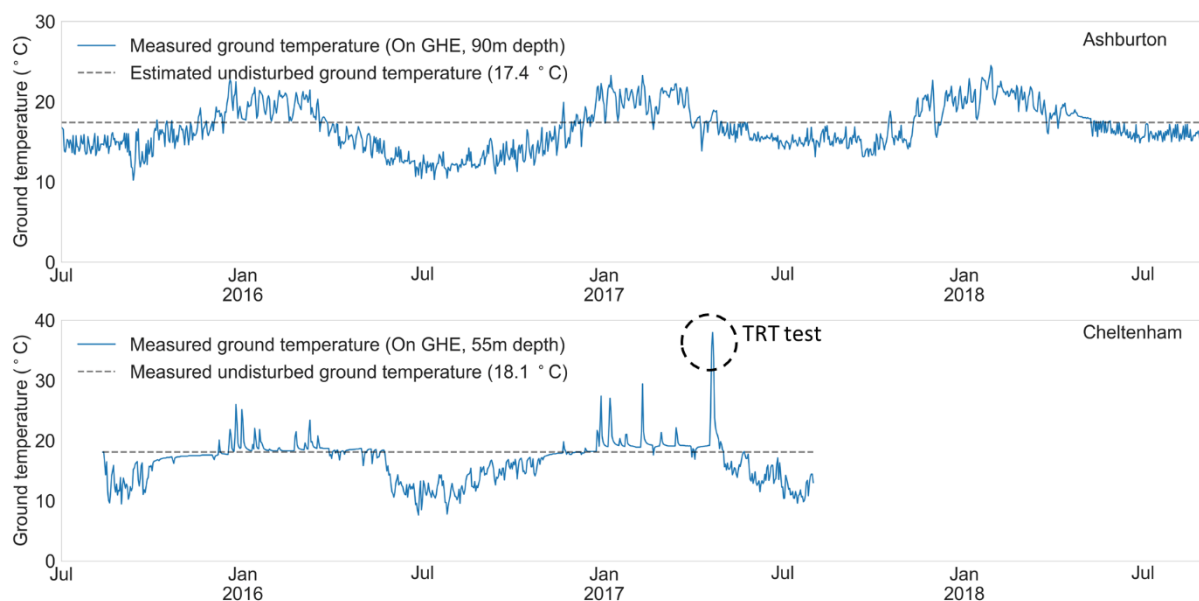


Figure 4-6: Daily measurement of ground thermal response at Ashburton and Cheltenham

By comparing the two-measured ground thermal responses in Figure 4-6, it can be observed that there is more temperature response/fluctuation at Ashburton than at Cheltenham since the former system is used more frequently than the latter system. Another difference is that the ground temperature at Ashburton increases slightly from year to year (slight upward trend), whereas the ground temperatures at Cheltenham tend to be relatively stable with respect to the measured undisturbed ground temperature.

It is interesting to note that the measured ground temperature at Ashburton increases from year to year even though the property is heating dominant (see Table 4-4). This increase in ground temperature can be observed relative to the estimated undisturbed ground temperature. A more frequent heating usage should reduce the ground temperature as more thermal energy is extracted during the heating season than rejected to the ground during the cooling season. This anomaly needs further consideration.

The distinct usage frequency of the GSHP systems between the two properties also has another impact on the ground thermal response. This is illustrated in Figure 4-7, where the ground thermal response for the first 6 months of measurement is presented along with the average daily thermal load applied to the ground. The ground temperature response at Ashburton closely matches the average daily thermal load pattern. When heating is provided to the building, the ground temperature decreases and vice versa.

On the contrary, even though the usage is less frequent and less intense than at Ashburton, the ground temperature at Cheltenham does not follow the average daily thermal load pattern closely. The ground temperature changes at Cheltenham seems to be much slower to respond to the applied thermal load. It is likely that this behaviour is caused by the Cheltenham's GHEs are placed in principally sand which has a much lower thermal conductivity than is likely for the Ashburton GHEs (see Table 4-3). On the other hand, because the thermal load demand during spring is very small, the ground temperature seems to recover towards its undisturbed level by early December. This ground thermal recovery allows the system to maintain relatively unchanged ground temperatures even though the monitoring data revealed that the usage is highly heating dominant.

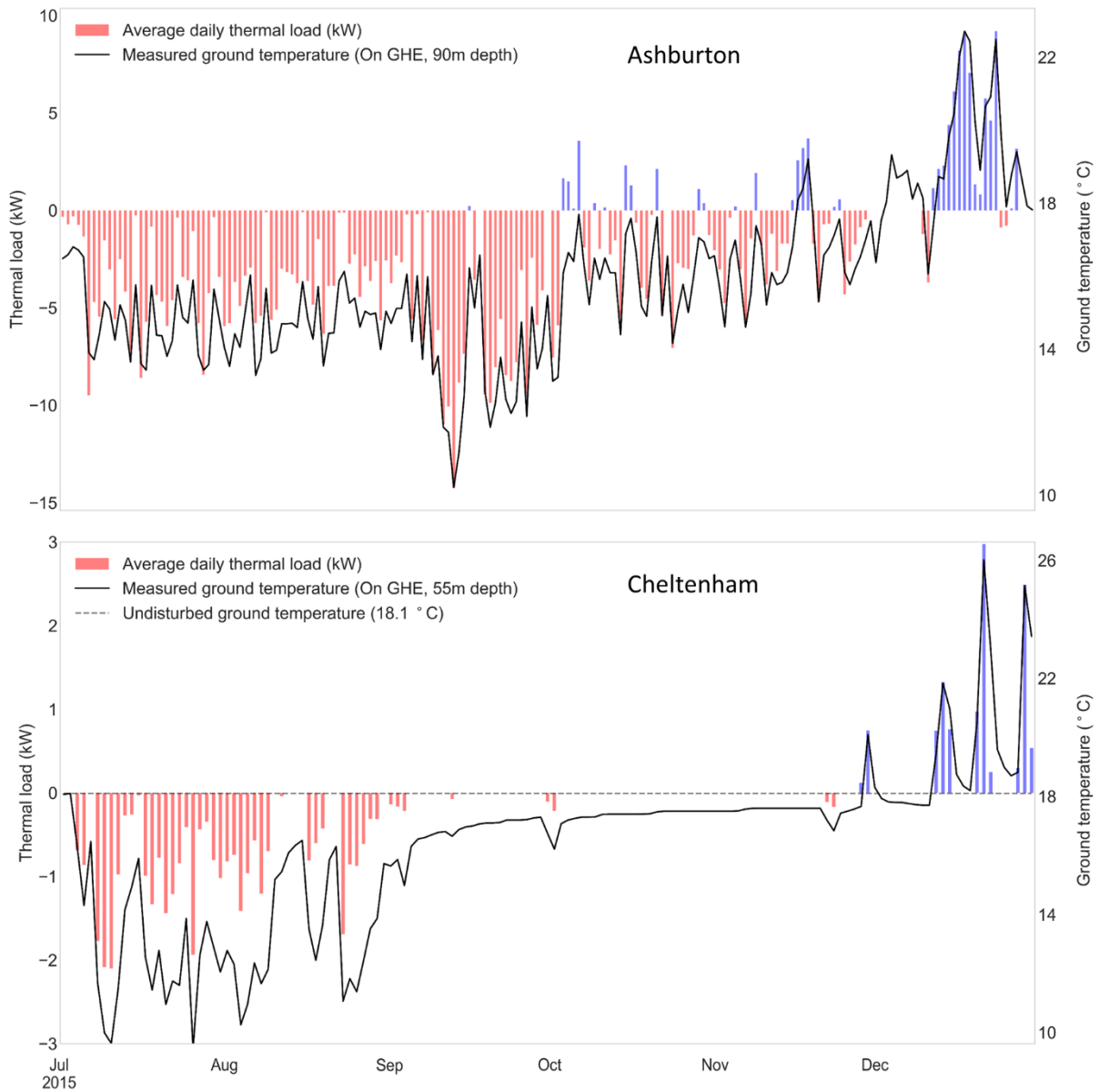


Figure 4-7: Ground temperature response and average daily thermal load in Ashburton and Cheltenham up to 31st December 2015

4.4.7 Impact of user behaviour on financial and environmental impact assessments

The distinct usage behaviour by the occupants in both properties can severely impact the financial and environmental assessment of the GSHP systems as discussed in this section. To illustrate this, financial and environmental metrics are computed based on the measured GSHP systems parameters. The GSHP systems in both properties are compared against a conventional system. Here an air source heat pump (ASHP) system is deemed as the most appropriate comparison.

Several financial and environmental parameters were assumed to conduct this analysis as shown in Table 4-5 below. The installation cost for the ASHP system at Ashburton (\$1,000/kW) was estimated to be more expensive than at Cheltenham (\$800/kW) because the system at Ashburton also needs to cover for pool and hot water heating. The year 2016 was selected for this financial and environmental analysis since a full heating and cooling cycle data were collected without any interruptions. The result of this analysis is presented in Table 4-6, and explained in detail next.

Table 4-5: Parameters used for financial and environmental assessment

Parameter (unit)	Value	Note
Electricity price (c/kWh)	27.6	Weighted average based on time of use and including GST [141]
Electricity emission factor (kg CO ₂ e/kWh)	1.17	Electricity emission factor for end-users in Melbourne [127]
Installation cost at Ashburton (\$)	60,000	Approximately from documentation, including supply and installation of GHEs, GSHPs and distribution systems
Installation cost at Cheltenham (\$)	30,000	Approximately from documentation, including supply and installation of GHEs, GSHPs and distribution systems
Installation cost for ASHP at Ashburton (\$)	32,000	Assume \$1,000/kW for a 32 kW system based on Lu et al. [41]
Installation cost for ASHP at Cheltenham (\$)	7,200	Assume \$800/kW for a 9 kW system based on Lu et al. [41]
SPF for ASHP	2.5	An assumed value based on Spitler et al. [18]’s VRF measurement on ASHRAE’s headquarter
SPF for GSHP system at Ashburton	3.7	For the year 2016. See Table 4-4.
SPF for GSHP system at Cheltenham	3.5	For the year 2016. See Table 4-4.

It is important to recognise that in 2016, the systems at Ashburton and Cheltenham were operated only for 45% and 6% of the year (See Table 4-4). Both of these values are lower than the expected usage of around 82% based on the bin method. Hence, a further comparison is conducted for the year 2016 between the measured (based on the data presented earlier in Table 4-4) and the estimated usage based on the bin method.

The bin method [10] suggests that heating and cooling are normally required when the outside air temperature is lower or higher than 15.6 and 19.4 °C (60 and 67 °F) respectively. Through this method and based on the peak GSHP capacity installed (see Table 4-3), the property at Ashburton is estimated to require around 84,011 kWh and 16,199 kWh of heating and cooling respectively, whereas the property at Cheltenham requires around 15,808 kWh and 5,206 kWh of heating and cooling respectively. This estimated thermal energy demand is much higher than the actual thermal energy measured at both properties in 2016. Operating the installed system at this higher frequency is likely to reduce the average annual SPF values compared to the measured values. For simplicity, the same SPF values (3.7 in Ashburton and 3.5 in Cheltenham) are used for this financial analysis based on the measured SPF in 2016. In this case, 27,084 kWh and 6,004 kWh of electricity are needed to run the GSHP system at Ashburton and Cheltenham respectively if they are operated all year around as recommended by the typical design based on the bin method.

The amount of electrical energy needed to run the ASHP systems can be estimated next. To do this, an assumed SPF of 2.5 (based on the work by Spitler et al. [18]) was used to calculate the amount of electricity needed to run the ASHP system at each property to provide equivalent thermal energy. The estimated ASHP's energy consumption for each scenario is presented in Table 4-6 where the ASHP system requires more electricity to run compared to GSHP system since the measured SPF for the GSHP system at either property is higher than the assumed SPF for the ASHP system. This higher electricity requirement further results in higher annual operating costs for ASHP systems compared to GSHP systems.

Table 4-6: Financial and environmental analysis for both properties

Parameter (unit)	Ashburton (measured)	Ashburton (bin method)	Cheltenham (measured)	Cheltenham (bin method)
Heating provided in 2016 (kWh)	48,378	84,011	2,471	15,808
Cooling provided in 2016 (kWh)	6,838	16,199	278	5,206
Electrical energy needed to run the GSHP (kWh)	14,840	27,084	780	6,004
Equivalent electrical energy needed to run the ASHP (kWh)	22,086	40,084	1,100	8,406
Capital cost difference to install a GSHP and an ASHP system (\$)	28,000	28,000	22,800	22,800
Annual operating cost difference between a GSHP and an ASHP system (\$)	2,000	3,588	88	663
Estimated payback period (years)	14	8	258	34
Annual energy consumption difference between a GSHP and an ASHP system (kWh)	7,246	13,000	320	2,402
Annual carbon emission saved by using a GSHP system over an ASHP system (kg CO ₂ e)	8,478	15,210	374	2,810

The capital cost required to install the GSHP systems is assumed to be more expensive than to install an equivalent ASHP system based on several assumptions outlined in Table 4-5. The extra costs represent the additional costs to install the GHEs, which are only needed in GSHP systems. However, it is important to note that the GSHP system installation cost at Cheltenham (~ \$30,000) is at the upper end of the typical installation cost for a 9 kW system found in Melbourne, which was mainly attributed to challenges arising from the geology on site encountered during the drilling process. Compared to the ASHP system, the GSHP system at Ashburton requires an additional \$28,000 (\$60,000 - \$32,000) and the GSHP system at Cheltenham requires an additional of \$22,800 (\$30,000 - \$7,200) capital costs. Similar method is used to calculate the differences in the annual operating costs between GSHP and ASHP systems for all 4 scenarios. For example, based on the bin method, the GSHP is estimated to require 27,084 kWh of electricity, while the ASHP requires 40,084 kWh of electricity. This means that the GSHP requires 13,000 kWh less of electricity, which is equivalent to around \$3,588 of operating cost savings annually.

The simple payback period is used as the financial indicator to compare the GSHP and ASHP system, where the payback period is calculated as the cost of the additional investment divided by the annual savings in cash flow. In this case, the GSHP system requires a higher capital cost but has lower annual operating costs compared to the ASHP system. One assumption made in this simple payback period calculation is to simplify that the SPF remains the same in each year (e.g., SPF for Ashburton stays constant as 3.7). This method is commonly used in literature to calculate simple payback period, such as the one used in [41, 97]. This is in contrast with the actual measured SPF that may change every year as observed in Table 4-4

Based on the actual installation costs and measured energy consumption of the system in 2016, the occupiers at Ashburton require 14 years to get a financial return on their GSHP system investment. In contrast, the property at Cheltenham offers next to no return for the occupiers and will require over 200 years for the occupiers to get a return on their investment. Even though a GSHP system consumes less electricity than a conventional system due to its higher efficiency, there is simply no financial savings to be gained if the system is hardly used.

A similar observation can be made regarding the estimated environmental savings in both properties. Both occupiers reduced their annual carbon emissions since the GSHP system require less electricity to run compared to the ASHP system. The adoption of the GSHP system can reduce carbon emissions in the Ashburton property by around 8,500 kg CO₂e per annum, in contrast to the property at Cheltenham which can save less than 400 kg of CO₂e.

The financial and environmental savings based on the actual run time presented above are significantly different than the estimated values based on a typical design method, such as the bin method, which assumes heating and cooling is needed all year round. If the occupiers follow this assumption and operate the systems at all times, a payback period of 8 and 34 years are expected for the system at Ashburton and Cheltenham respectively, assuming that the SPFs remain unchanged even with this much higher usage frequency. Additionally, the low actual run time of the systems at Cheltenham further resulting in severely minimal carbon emission savings compared to the estimated possible savings based on a typical design method. The scenario described here is an example of the pre-bound effect, where the actual monetary saving from an investment in an energy-saving technology is much lower compared to the expected savings, due to an overestimation of the predicted energy consumption (by not accounting for users' behaviour) at the start of the investment.

The case study exemplified here suggests that the bin method may not be the best design approach for residential GSHP systems under temperate climate conditions. The moderate temperature in such climate allows residential occupiers to switch off their heating and cooling system for significant parts of the day and the year. The use of air conditioning systems can be reduced further depending on user behaviour. Hence, another or a modified design method may be required. This pattern of usage may be better served through a hybrid GSHP system where GSHP systems can provide the base load thermal demand with conventional systems servicing the hotter and colder periods of the year. Such system has smaller GSHP system component which lower the capital costs required and improved the overall financial returns for building's occupiers.

4.5 Conclusions

This chapter provides a detailed analysis of two residential GSHP systems in Melbourne, Australia. These were two out of ten different properties which had their GSHP systems monitored, and represented one of the highest usage properties (run time = 36%) and one of the lowest usage properties (run time = 6%). Some key observations made from the monitored data are:

- For all properties monitored, the percentage of the time the systems were operating was small
- The GSHP systems have a seasonal performance factor (SPF) between 3.3 and 4 in both properties, but a coefficient of performance between 3.8 and 4.7.
- The SPFs observed in this experiment are within the range of the observed SPF between 3 and 4 from other GSHP systems monitored elsewhere as reported in the literature.
- Despite the proximity of both properties, the property at Ashburton is used significantly more than the property at Cheltenham. This suggests that thermal energy consumption may be affected by both the climatic conditions and user behaviour.
- The GSHP system usage at Ashburton is consistent throughout the year. Some heating usage can be observed during summer months, but this might be due to hot water generation and pool heating. In contrast, the property at Cheltenham typically requires only heating or cooling depending on the season. Furthermore, minimum heating and cooling usage were observed in Cheltenham during spring and autumn.
- Closer inspection on the user behaviour in each property reveals that the heating and cooling usage pattern at Ashburton resembles a typical 9 to 5 worker, while the system at Cheltenham closely resembles a stay at home user. This observation matches the demographics of the actual occupiers at these respective properties. Furthermore, the occupier at Cheltenham also applies a larger set point temperature band than the occupier at Ashburton, which results in significantly lower heating and cooling usage at Cheltenham.
- The GSHP system at each property is operated with a contrasting usage pattern. The occupiers at Ashburton tends to leave their system on overnight while turning it off during the day when they are away for work. This represents a usage pattern of a high energy end-user. On the other hand, the property at Cheltenham is occupied during the day, which shows most of their energy use, while the system is switched off at night. Turning off the system at night resulting in high energy savings for the occupiers at Cheltenham.
- The low usage of the system at Cheltenham allows the ground temperature to return towards the undisturbed ground temperature especially during a period when the GSHP system is not used for several consecutive days.
- Finally, it was concluded that even though GSHP systems can operate relatively efficiently under Australian climatic conditions, the financial and environmental savings generated from this investment are greatly dependant on user behaviour. No savings can be gained if the system is used only for a few hours of the year.

4.6 Acknowledgement

The authors acknowledge the financial support for this project by the Victorian Government's Department of Environment, Land, Water and Planning. They are also grateful to all the property owners/tenants who allowed monitoring of their systems along with associated installers.

5 Comparative costs of ground source heat pump systems against other form of heating and cooling for different climatic conditions

5.1 Overview and structure

The monitored data from Chapter 4 indicates that the temperate climate in Melbourne results in moderate heating and cooling demand in Melbourne. In such a condition, a hybrid combination between GSHP and conventional systems may be preferred for homeowners if they want to install the most cost-effective heating and cooling system. A hybrid GSHP (HGSHP) system is that where a GSHP system is sized to provide the baseload thermal energy for a building and this system is supported by a conventional system during the hottest and coldest days of the year. As such, this chapter investigates the financial feasibility of HGSHP systems.

In this chapter, the lifetime costs of GSHP systems are compared with HGSHP and conventional systems. This study is expanded to seven major Australian cities as well as more extreme climate overseas to cover a wide range of possible climatic conditions. Sensitivity analysis of several key design parameters was also conducted.

A paper titled “Comparative costs of ground source heat pump systems against other form of heating and cooling for different climatic conditions” based on this chapter has been submitted to the journal *Building and Environment*. However, to maintain consistency with thesis the full text of the paper is presented here. This chapter and publication are the author’s original work. Co-author authorisation forms have been included in this submission.

5.2 Introduction

Thermal energy accounts for over 50% of residential and commercial energy used globally, and natural gas and electricity are the most common sources of energy for space heating and cooling [142]. To achieve long term energy sustainability, electricity and natural gas consumption need to be reduced and ground source heat pump (GSHP) technology can contribute to this endeavour. Details about GSHP systems can be found elsewhere [11, 19, 143]. Typically, GSHP systems are more efficient than traditional heating and cooling systems as is indicated by generally higher yearly-average coefficients of performance (CoP). A residential GSHP system typically shows a CoP of about 4 which means that for every 1 kWh of electricity consumed about 4 kWh of thermal energy will be supplied to a building. In contrast, conventional heating and cooling systems such as reverse cycle air conditioners (RCAC) typically have a CoP of less than 4 [17, 18, 25, 26]. For example, Spitler et al. [18] have reported a monitored Variable Refrigerant Flow system (another type of conventional cooling system) performed at a CoP of 2 in heating and 2.5 in cooling in a commercial building. Systems using electric heaters or gas furnaces directly to provide space heating operate at equivalent CoPs (efficiencies) of less than 1 and cannot provide cooling.

With these higher CoPs for GSHP systems, and depending on several other factors, the use of GSHP systems for heating and cooling has the potential to not only reduce electricity and gas consumption but also to do so with significantly reduced operating costs. However, relatively high capital costs and longer payback periods are often seen as potential roadblocks for property owners to install GSHP systems [27, 41, 144].

The financial attractiveness of a GSHP system can be increased further by using a hybrid ground source heat pump (HGSHP) system. Such a system uses a GSHP system to provide the base load thermal energy to a building with the balance provided by a conventional system for the hotter and colder periods of the year. These systems take advantage of the relatively low installation costs of conventional systems and the relatively low operating costs of GSHP systems to potentially make HGSHP systems even more attractive [97-99].

Over recent years, the feasibility of HGSHP systems has been examined numerically and experimentally [14, 97-104, 145]. In these studies, an HGSHP system is usually sized to minimise the net present cost (NPC) of the system by adjusting the proportion of total heating and cooling loads provided by a GSHP system and a conventional system. This proportion is referred to as a *shave factor*. A shave factor of 60% means the GSHP system provides 60% of the peak load, while the conventional system provides the remaining 40%.

However, these studies were conducted mainly for the cooler northern hemisphere countries, such as in the USA, Canada, UK and Romania. This chapter considerably extends the work of Aditya et al. [14] and presents comparative costs of GSHP and HGSHP systems under a range of different climatic conditions, as exemplified by those encountered in Australia, along with the conditions encountered in Singapore, London and Montreal. A greater range of input parameters, such as ground thermal conductivity, energy pricing and drilling costs, is considered and the sensitivity of the results to variations in some of the factors affecting costs are also examined and presented.

5.3 Data and methodology

Ten major cities have been chosen to represent some of the different climatic conditions encountered in Australia and worldwide. The Australian cities are Adelaide, Brisbane, Cairns, Hobart, Melbourne, Perth and Sydney whose locations are indicated in Figure 5-1. Australia is in the southern hemisphere, so the hottest conditions are generally found in the north of the country. Additionally, London, Montreal and Singapore (shown in Figure 5-1), have been added to provide an international perspective and a means for comparison with Australian conditions. London has been selected as it has a similar climate to some southern Australian cities. Montreal and Singapore have been selected to represent highly heating and cooling dominant conditions.

5.3.1 Climatic conditions and thermal loads

Following the methodology adopted in an earlier study [14], the hourly outside air temperature (OAT) data were retrieved from Meteonorm [146]. For simplicity, the undisturbed ground temperature at shallow depth (T_g) was assumed to be the local average annual OAT plus 2 °C as described in IGSHPA [10]. In reality, other factors such as solar radiation and moisture evaporation can affect the undisturbed ground temperature at shallow depths [147]. At this shallow depth (50 to 200 m where the ground heat exchanger is typically installed), it is also assumed that the geothermal gradient has no effect.



Figure 5-1: This study considers a range of climatic conditions, including those found in seven Australian cities and three cities in other continents

The building used for this analysis was modelled by using EnergyPlus V8.7 [148], a widely used open-source energy simulation program. A typical Australian two-bedrooms residential dwelling with a total floor area of 150 m² was selected for this case study. The key characteristics of this building are described in Table 5-1 below. It is important to note that this building has relatively poor insulation criteria (high U values). The Building Code of Australia [149, 150] specifies the same minimum insulation requirement across Australian climates, perhaps due to the temperate climate encountered here.

This idealised building is assumed to be located across the 10 cities considered for simplicity. This same building most likely does not meet the insulation criteria for buildings located in warmer or colder climate overseas. However, utilising the standard Australian building design code (with relatively low building insulation) will estimate the worse case condition for the same building under the London, Montreal and Singapore climates (i.e., the real buildings should have an actual thermal load lower than the one assumed in this work). Since the focus of this chapter is to investigate the impact of climatic conditions on the economic feasibility of HGSHS systems, this assumption would appear conservative.

Table 5-1: Description of the case study building including parameters used for EnergyPlus simulation

Building characteristics	Value	Note
Building floor area (m ²)	150	1 living room, 2 bedrooms
Floor height (m)	3	
Number of occupants	4	
External wall U-value (W/m ² K)	0.987	Concrete wall & gypsum, including insulation
External roof U-value (W/m ² K)	0.285	Metal decking, including insulation. Flat roof
External window U-value (W/m ² K)	6.424	Glass window
Zone ventilation (air change per hour)	1	20% more than the minimum outdoor area required in Australia (0.35 L/s/m ²), AS 1668.2-2012 [151]
Indoor heating thermostat set point (°C)	20	
Indoor cooling thermostat set point (°C)	22	
Occupancy		Assume all year around
Weather data		TMY file available at each location from Meteonorm [146]

The hourly heating and cooling peak load at each location were calculated using the above parameters. The software calculated both sensible and latent cooling load using the weather data at each location. Therefore, the cooling load presented in this work refers to the total cooling load which accounts for the humidity at each location. Based on the above information and methodology, Table 5-2 presents an overview of the input parameters and the peak heating and cooling load for each city.

5.3.2 Heating and cooling options

The Australian Bureau of Statistics [152] reported that for residential heating, 38% of residents use electricity and 30% use gas, while for cooling, 49% of residents use an air conditioner. A similar statistic from the U.S. Energy Information Administration [2] indicates that for residential heating, 36% of residents use electricity and 47% use gas, while for cooling, 87% of residents use an air conditioner. Today, most air conditioners are reverse cycle air conditioners (RCAC). As such, the following heating, ventilation and air conditioning (HVAC) system options in this work are (Options 1 to 5):

1. Heating and cooling by an RCAC;
2. Heating with a gas furnace and cooling by an RCAC;
3. Heating and cooling with a GSHP;
4. Heating and cooling by HGSHP system (HGSHP1) with a GSHP and an RCAC;
5. Heating and cooling by HGSHP system (HGSHP2) with a GSHP, a gas furnace for heating and an RCAC for cooling.

The CoPs of RCAC and GSHP systems can vary throughout the year because of the variations in OATs for RCAC systems as well as the ground temperatures around ground heat exchangers (GHEs) for GSHP systems. A high-performance RCAC (Fujitsu AOTG30KMTA) and GSHP (Water Furnace NSKW06) unit available off the shelf were chosen for the analysis to make this case study more realistic.

The hourly CoP of the RCAC system was computed by using the manufacturer's datasheet as well as the OATs at each location. Computing the hourly CoP of the GSHP system is more complicated, where the hourly ground temperature and the entering water temperature (EWT) to the GSHP need to be computed first. Those values were simulated using the borehole thermal resistance provided in Table 5-3 and utilising the methodology adapted from Weeratunge et al. [96], based on the original Infinite Line Source model [50]. These simulated EWT values are used in conjunction with the GSHP's datasheet to calculate the hourly CoP for the GSHP system. These hourly CoPs for RCAC and GSHP system are used for the analysis presented in the subsequent section. The Python code used for this analysis is included in Appendix C.

For simplicity, the average seasonal CoPs (SCoP) for the RCAC and GSHP system at each location are computed and presented in Table 5-2 presents the computed average seasonal CoPs (SCoP) for the RCAC and GSHP system at each location. The results indicate that both GSHP and RCAC system have a lower SCoP at locations that are highly heating or cooling dominant, such as at Montreal and Singapore. A constant efficiency value of 0.9 is assumed for gas furnace since this parameter represents a constant rate of gas combustion.

Table 5-2: Summary of locations, ground temperatures, peak heating and cooling loads, average seasonal CoP of RCAC and GSHP system

	Latitude (degrees)	Longitude (degrees)	Estimated average T _g at shallow depth [^] (°C)	Estimated peak heating/cooling load (kW)	SCoP of RCAC (-)	SCoP of GSHP (-)
Adelaide	34.9 °S	138.6 °E	18.7	7.4/6.7	2.5	4.6
Brisbane	27.5 °S	153.0 °E	22.2	7.2/7.2	2.6	4.7
Cairns	16.9 °S	145.8 °E	26.5	3.3/9.0	2.5	4.2
Hobart	42.9 °S	147.3 °E	12.9	8.6/5.6	2.5	4.2
Melbourne	37.8 °S	145.0 °E	16.5	8.4/5.5	2.5	4.5
Perth	32.0 °S	115.9 °E	19.9	7.8/8.1	2.6	4.7
Sydney	33.9 °S	151.2 °E	20.1	5.8/7.3	2.6	4.7
London	51.5 °N	0.1 °W	13.1	11.7/4.8	2.3	4.5
Montreal	45.5 °N	73.6 °W	7.4	21.9/8.3	2.1	4.3
Singapore	1.4 °N	103.8 °E	28.8	0.0/9.1	2.3	3.4

[^] average annual OAT plus 2 °C;

For the GSHP and HGSHP systems, the required ground heat exchanger (GHE) lengths are calculated based on the ASHRAE design approach using Equation (9) [60]. The parameters in Equation (9) are defined in Table 5-3 below.

$$L_{GHE} = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_c R_{6h}}{\frac{(T_i + T_o)}{2} - (T_g + T_p)} \quad (9)$$

Geological and hydrogeological conditions vary within cities, so it is possible to find similar conditions across different case locations. Therefore, the design parameters initially used in this work assume that the same ground conditions (but not T_g) apply to all the cities for easier comparison. Nevertheless, the ground thermal conductivity value will be varied in Section 5.4.6.

The design EWT in each city is based on the T_g at each location as recommended in Kavanaugh and Rafferty [56]. Although not perfect, this method is the starting point for GSHP system design, where this design parameter represents a trade-off between GHE design length and system's efficiency. Using EWT value that is pegged to T_g allows some generalisation between all cities and climatic conditions considered. All the design parameters are summarised in Table 5-3 below.

Table 5-3: Parameters used for sizing of GHEs

Design parameter (units)	Description	Value
q _h , q _m , q _y (kW)	Peak hourly, monthly average and yearly average ground loads	Calculated based on building thermal demand, heating and cooling shave factors, and CoP of GSHP
R _b (m.K/W)	Effective thermal resistance of the borehole	0.103
λ (W/m.K)	Ground thermal conductivity. It is used to calculate R _{6h} , R _{1m} and R _{10y}	2.5
R _{6h} (m.K/W)	Effective thermal resistance of the ground to 6 hours of ground load	0.106
R _{1m} (m.K/W)	Effective thermal resistance of the ground to 1 month of ground load	0.146
R _{10y} (m.K/W)	Effective thermal resistance of the ground to 10 years of ground load	0.153
T _g (°C)	Undisturbed ground temperature at shallow depths	Listed on Table 5-2
T _{i,h} (°C)	EWT to GSHP in heating operation	T _g – 5.5 °C (T _g – 10 °F)
T _{i,c} (°C)	EWT to GSHP in cooling operation	T _g + 11.1 °C (T _g + 20 °F)
T _p (°C)	Temperature penalty	0 (GHE is thermally independent)

5.3.3 Cost comparisons

In this work, the parameters and assumptions used for the cost comparisons are based on those presented by Lu et al. [41]. These parameters are summarised in Table 5-4 below, where it is (initially) assumed that installation costs, inflation rates and discount rates for electricity and gas, and life spans of the systems are kept constant for all case study locations to facilitate comparisons. The life span of a GSHP system is assumed to be 20 years, while the life spans of both gas furnace and RCACs are assumed to be 10 years each. This means that both conventional systems will need to be replaced once over the 20 years design life. The replacement costs of these systems are assumed equal to the original price. In this work, maintenance cost is excluded from the analysis since this value is expected to be small in comparison to the installation and operational costs of the systems. For example, maintaining a residential heating and cooling system (e.g., systems check-up and GHEs flushing) may require around half a day of labour, which represents around 5% of the GSHP systems annual operating cost. Despite that, it is important to acknowledge that the maintenance cost of GSHP systems is likely to be lower than conventional systems [145]. The assessment is presented in Australian dollars (A\$). One A\$ is approximately US\$ 0.72 at the time of writing.

The retail prices of electricity and gas across the ten cities considered are shown in Table 5-5. These prices were collected from various major energy retailers that operate in the chosen cities [141, 153-159] and have been calculated based on the weighted price average during peak, off-peak and shoulder periods. The electricity price in Australia can vary as much as from about 20 c/kWh in Hobart to about 31 c/kWh in Adelaide. In contrast, gas prices in Australian cities are more consistent and between 9 and 13 c/kWh. The average electricity prices for London and Singapore are similar to the lower end of the Australian range. However, the electricity price in Montreal is much lower since the electricity for this city is mostly sourced from cost-effective hydro power stations [158]. Gas prices in London and Montreal are also significantly lower than in Australian cities.

Table 5-4: Parameters assumed for cost comparisons (based on [10])

Parameter (units)	Value	Note
Cost of drilling (A\$/m)	80	Borehole installation
Cost of GSHP (A\$/kW)	2,000	Equipment and installation of the system
Cost of gas furnace (A\$/kW)	500	Equipment and installation of the system
Cost of RCAC (A\$/kW)	1,000	Equipment and installation of the system
Electricity inflation rate (%)	6.2	
Gas inflation rate (%)	6.14	
Discount rate, r (%)	3.5	
Life span of GSHP system (years)	20	
Life span of gas furnace and RCAC (years)	10	
Replacement of gas furnace and RCAC	Every 10 years	
Design life (years)	20	

Table 5-5: Electricity and gas price considered

	Electricity price (c/kWh)	Gas price (c/kWh)	Electricity/Gas price ratio (-)
Adelaide	31.3	13.0	2.4
Brisbane	22.0	10.6	2.1
Cairns	22.0	10.6	2.1
Hobart	20.2	12.6	1.6
Melbourne	27.6	9.4	2.9
Perth	27.2	10.3	2.6
Sydney	23.8	12.6	1.9
London	21.5	4.9	4.4
Montreal	7.4	1.2	6.2
Singapore	20.3	16.8	1.2

Note: price shown for international cities are in A\$ equivalent

The Net Present Cost (NPC) has been adopted as the principal indicator for the various heating and cooling options considered. The NPC is calculated as follows:

$$NPC = \sum_{t=1}^{20} \frac{C_t}{(1+r)^t} \quad (10)$$

where C_t represents the cash outflow at time t which can be a capital cost or an operating cost. This cost at time t will be discounted back at interest rate r (3.5% see Table 5-4) over a 20 year design life of the system. It follows that the NPC represents the present value of all cash outflows including the installation, operation and replacement (if necessary) of each system for a 20 year design life of the system.

The analysis in this chapter has not considered the environmental benefits of HGSHS systems as this will be part of the next chapter.

5.4 Results and discussion

5.4.1 Annual thermal demand

Following the simulation in EnergyPlus, Figure 5-2 presents the calculated annual thermal demand in each of the ten cities of this study. These systems run as needed with the aim to maintain an indoor temperature between 20 and 22 °C. As expected, climatic conditions significantly affect a building's energy needs. All of the cities are heating dominant, except Brisbane, Cairns and Singapore, where they are cooling dominant. This simulated thermal load is in agreement with ASHRAE's climate zone classification based on the heating and cooling degree days at each location [160]. For example, the simulation results in Table 5-2 suggest that Singapore and Montreal have the highest annual cooling and heating requirements. This matches with ASHRAE standard 169-2013 where Singapore and Montreal are listed as the location with the highest cooling and heating degree days (Singapore is climate zone 0A and Montreal is 6A).

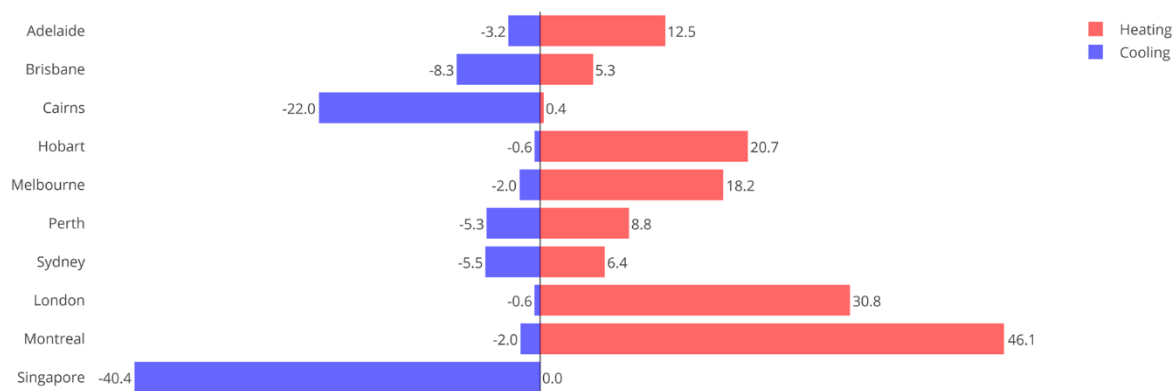


Figure 5-2: Annual heating and cooling demands in MWh of a typical 10 kW system. Negative values indicate cooling

5.4.2 Capital and operating costs for conventional and GSHP systems

This section investigates the capital and operating costs for conventional and GSHP systems (Options 1 to 3 listed in Section 5.3.2) following the methodology in Section 5.3. These costs are summarised in Figure 5-3. Since heating is not needed in Cairns and Singapore, only one conventional system (Option 1 - RCAC) is presented.

Figure 5-3a shows that for a 20 year life span of each system, the *capital* costs (plant and GHE costs) of a GSHP system is always higher than the cost of conventional systems even after accounting for the replacement costs of the latter systems if needed. Most of the capital costs of the GSHP systems arise from the GHE installation costs which include drilling of boreholes for the GHEs. This GHE cost is based on the calculated GHE lengths using Equation (9), where the lengths are mainly determined by the unique thermal load pattern in each city/climate as well as the undisturbed ground temperature. The GHE length requirements vary as much as 181 m in Sydney to 590 m in Montreal. In general, the cities with a more unbalanced thermal load (eg: Montreal) need longer GHE lengths to allow for a large amount of heat to be dispersed or extracted into the ground without compromising the efficiency of the system.

It is also important to recognise that the GSHP systems at London, Montreal and Singapore require significantly more GHE length compared to the Australian cities. The reason behind this is that these three cities have more extreme climates, which means that to heat or cool the same house requires a bigger heating and cooling system, for example, the peak heating load in Montreal is more than double the peak heating load in Hobart (See Table 5-2).

Overall, once this different peak heating and cooling load requirements are accounted for, then all of the cities require around the same borehole heat transfer rate of around 30 to 40 W/m of GHE length. These values are calculated from the peak thermal load requirement divided by the calculated GHE length, for example, for the case in Sydney, the peak load is 7,300 W and the required GHE length is 181 m. This equates to the heat transfer rate of 40 W/m. These values are lower compared to the typical rule-of-thumb of 50 to 80 W/m outlined by Banks [161].

The combination of a gas furnace and RCAC system (Option 2) is slightly more capital intensive as two systems need to be installed compared to the case of just a single RCAC system (Option 1). Property owners in Australia used to install two different systems because the unit price of gas used to be significantly lower than the unit price of electricity (before significant gas price increases occurred over the last few years). Hence, two different systems are often used for heating and cooling buildings in Australia. Figure 5-3a shows that the total plant costs of GSHP and RCAC systems are similar even though the cost of the full GSHP system is double the cost of the RCAC system (see Table 5-4). The reason behind this is that as RCAC systems have a shorter life, and they need to be replaced (as explained in Section 5.3.3 and Table 5-4). Hence, the costs shown here are the costs for buying two 10 kW RCACs to provide a system life span of 20 years (one installed initially and one to be used at the 10th year mark), which is equal to the costs for buying one 10 kW GSHP for a life span of 20 years.

However, it should be noted that the capital costs required for the GSHP systems are usually higher compared to either of the conventional systems since the GSHP system also requires the GHE for it to work.

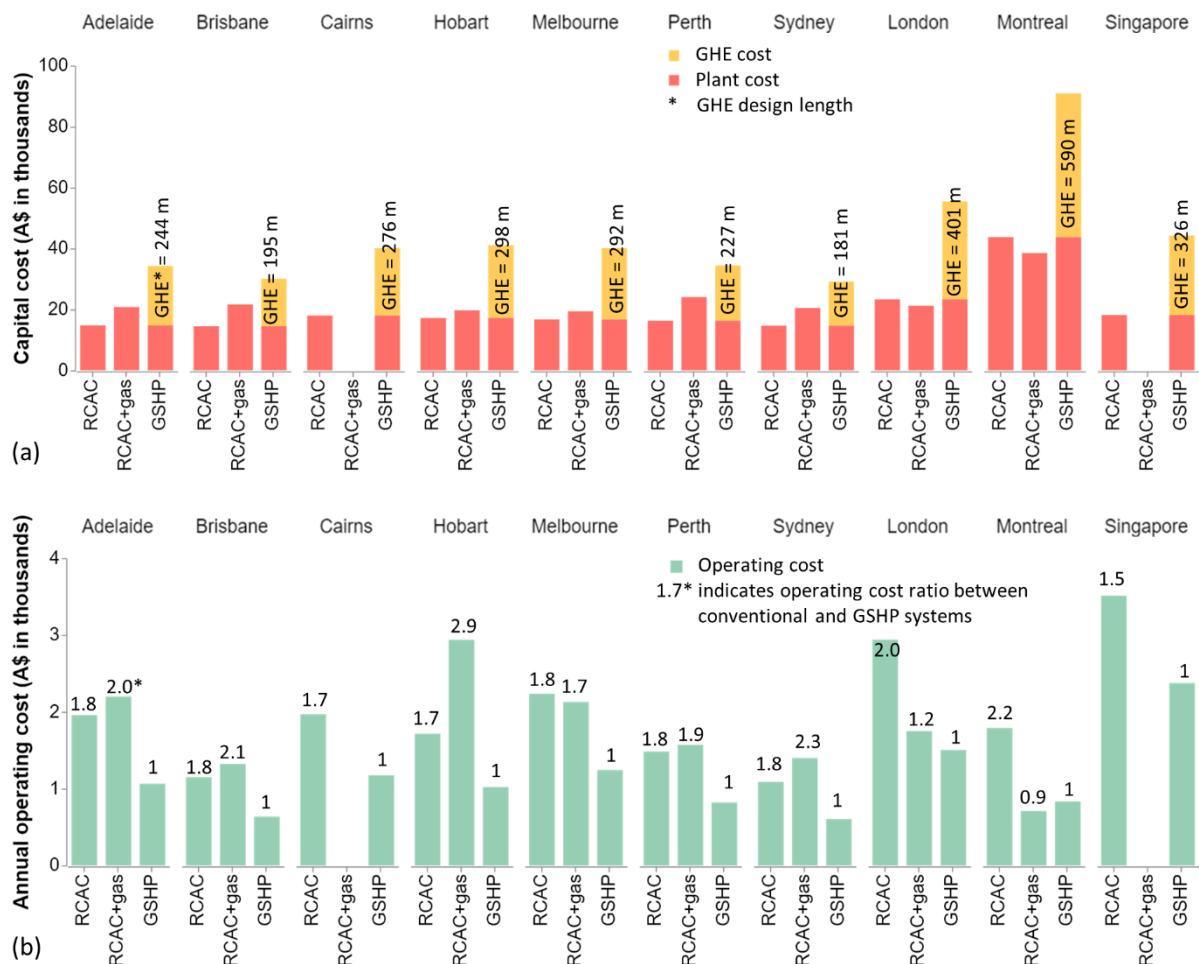


Figure 5-3: a) Capital costs and b) annual operating costs in A\$ for the 10 cities considered

The operating costs presented in Figure 5-3b only account for GSHP power consumption without considering the power consumption of circulation pumps (approximately 10% of operating costs), which is relatively small for small systems. Government financial incentives, where they may exist (e.g., Canada, UK) are not considered here either. The operating costs of the GSHP systems vary between about A\$600 and about A\$2,400 per year depending on the location (Figure 5-3b). The operating costs of GSHP systems are the lowest compared to the other heating and cooling options analysed here since it is generally the most efficient system. One exception is for a gas furnace and RCAC system in Montreal where it has a lower operating cost than a GSHP system. This is mainly due to the unit price of gas in Montreal being six times cheaper than the unit price of electricity (see the energy price ratio in Table 5-5), hence it is cheaper to heat by using a less efficient natural gas furnace rather than using a more efficient GSHP or RCAC system powered by electricity.

To better illustrate the differences between the operating costs of different options, Figure 5-3b also presents the operating costs when they are normalised with respect to the operating cost of GSHP systems in each city. A normalised cost of 1 represents the costs to operate the GSHP systems for each city. The normalised operating costs of RCAC systems in all the cities are between 1.7 and 2.2, depending on the relative efficiency comparison between GSHP and RCAC system.

The normalised operating cost for gas furnace and RCAC systems are not the same in all the cities, varying from 0.9 to 2.9. This cost differential is due to the variation of gas and electricity prices and the different heating and cooling requirements in each city. In Hobart, the normalised cost for the gas furnace and RCAC system is the highest (2.9) amongst all cities considered because most of the energy usage is for heating (20.7MWh - see Figure 5-2). Since this heating is provided by a less efficient and relatively more expensive gas furnace, the heating cost is significantly higher compared to using a more efficient GSHP system. This result indicates that switching from a gas furnace to a GSHP system in Hobart will lead to the highest operating cost saving. In contrast, switching from a gas furnace to a GSHP system in Montreal would have the opposite effect, although not as large as for Hobart.

The NPC for each heating and cooling system option considered in this section was calculated to compare the costs over a 20 year life span. The NPC represents the present value of all outgoing cash flows incurred to install, replace (if necessary) and operate over the 20 year life span of a system. Figure 5-4 shows GSHP systems generally have the lowest NPC compared to conventional heating and cooling systems. For example, installing a GSHP system instead of a RCAC and gas furnace in Hobart can save homeowners up to about A\$27,000 over the 20 year life span of the system (note an NPC ratio of 1.4 for 'RCAC+gas' in Hobart, where the NPC of a 'GSHP' system is about \$68,000 for the 20 year life span considered).

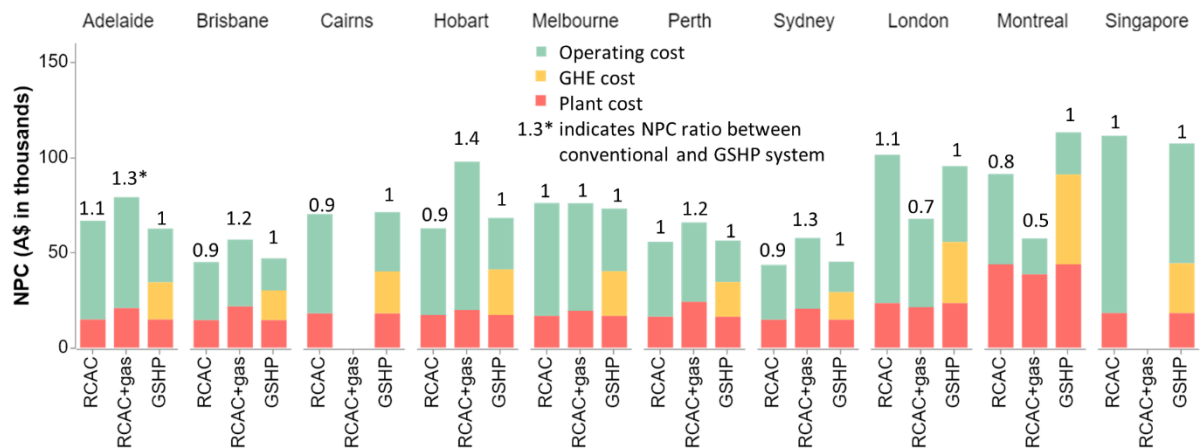


Figure 5-4: Net Present Costs in A\$ for the 10 cities considered

From Figure 5-4, GSHP systems usually have similar lifetime costs compared to conventional systems. However, GSHP systems are a cheaper option compared to RCAC and gas furnace systems, except those in London and Montreal since their gas prices are much cheaper compared to the relative price of electricity.

5.4.3 Hybrid ground source heat pump systems

The previous section demonstrates that GSHP systems can be used to provide efficient and cost-effective heating and cooling options for a wide range of climatic conditions. However, the high capital costs under current market and some climatic conditions can make GSHP systems a less attractive option for investment because their NPC is not always significantly less than the NPC of conventional systems. One way to take advantage of the generally low operating costs of GSHP systems and reduce the overall capital costs of the heating and cooling system is by installing a hybrid system.

A hybrid ground source heat pump (HGSHP) system is one where a GSHP system is sized to provide baseload thermal energy for a building which is topped up by a conventional system during the hottest and coldest days of the year. Figure 5-5 illustrates the energy provided by a GSHP in a hybrid configuration in Sydney, a fairly balanced thermal load scenario. This scenario is when the total annual heating is roughly equal to the total annual cooling requirement. In this case, the building in Sydney has the closest to a balanced load, where it requires 5.5 MWh of cooling and 6.4 mWh of heating annually.

If a GSHP system at this location were to be sized to provide 50% of the peak heating and cooling load (a shave factor of 50% giving 2.9 kW and 3.7 kW peak heating and cooling loads respectively), the GSHP system can provide around 92% of the thermal energy requirements. This is represented by the blue and red areas in Figure 5-5. The remaining 8% of the annual thermal requirement are provided by conventional system (they grey area in Figure 5-5). The grey areas represent the relatively short periods that require additional top-up with a conventional system. For all ten cities considered in this study, 82% to 94% of the annual thermal demand can be met if a 50% heating and cooling shave factor is applied, which in turn lowers the GHE length required and further reduces the capital cost of the installation.

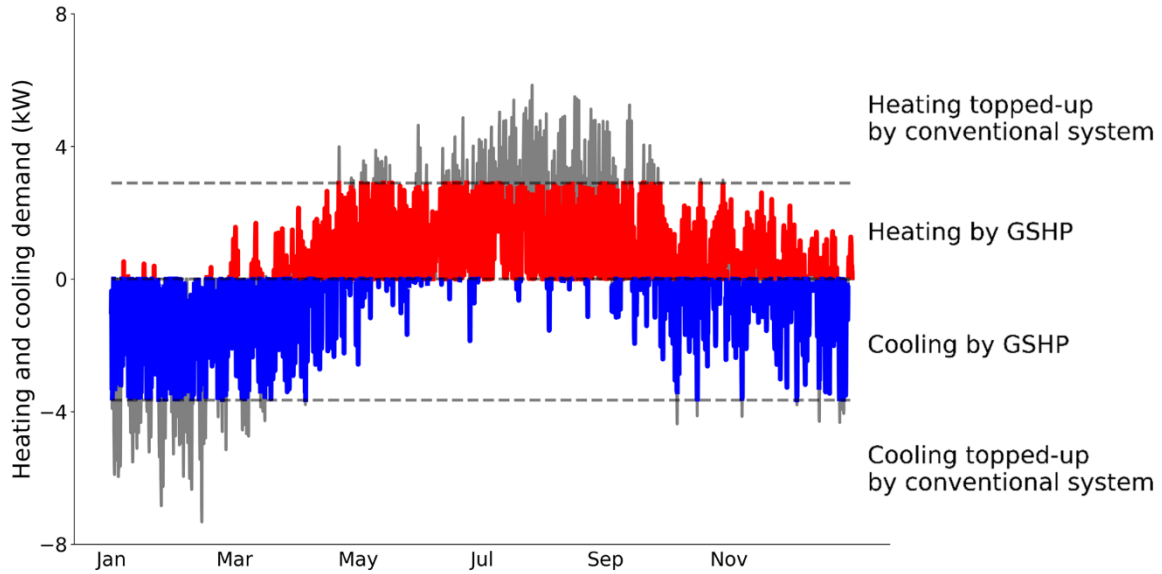


Figure 5-5: Illustration of an HGSHP system in a fairly balanced thermal load scenario (in this example, in Sydney) sized to meet 50% of peak heating and cooling power demands

This section explores the HGSHP sizing method where the lifetime cost of heating and cooling is represented by the minimised NPC over its 20 year life span, similar to the method presented in Mikhaylova et al. [98] and Aditya et al. [14]. The NPC is further normalised by the total amount of heating and cooling energy provided to a building over a 20 year design life to give the Total Normalised Cost (TNC) in A\$/MWh as follows:

$$TNC = \frac{NPC}{Total\ thermal\ energy\ provided\ by\ the\ system} \quad (11)$$

The use of TNC allows a direct cost comparison for different locations based on the amount of thermal energy produced by the system. This concept is similar to the “levelised cost of electricity” [162], but applied for thermal energy, where TNC provides a measure of lifetime cost to generate one MWh of heating or cooling energy. Two HGSHP systems are considered in this chapter in addition to the conventional and GSHP systems (Option 1 to 3) discussed previously. The first HGSHP system, HGSHP1 (or Option 4), is a system where the baseload demand is supplied by a GSHP system and supported by an RCAC. The second system, HGSHP2 (or Option 5), is a GSHP system which is supported by both a gas furnace for heating and an RCAC for cooling. For each HGSHP system, the TNC is calculated for different heating and cooling shave factors varying from 0% to 100% with a step size of 2% to cover a range of configurations. The HGSHP systems here are calculated by using the same design, cost and price parameters described earlier in Table 5-3 to Table 5-5, with no additional costs arising from the complexity of installing HGSHP systems over conventional ones since these costs should be minor for residential systems.

Each shave factor combination represents a GSHP system with a unique heating and cooling peak load combination as a proportion of a 10 kW system. The GHEs supporting these GSHP systems must be sized according to these peak load combinations, but then only the critical sizing is kept in the design for installation and costing. For example, if an HGSHP system in Sydney is sized to meet 30% and 80% heating and cooling shave factors, the GSHP needs to provide 1.7 kW heating and 5.8 kW cooling peak load respectively. To provide 1.7 kW peak heating load under Sydney climatic conditions, 66 m of GHE length is required, while to meet 5.8 kW of cooling load, 155 m of GHE

length is required. In this case, 155 m of GHE needs to be installed and this value is subsequently used to calculate the GHE installation costs. A similar assumption is made for the cost to install the GSHP, where the larger capacity (5.8 kW) needs to be installed.

The results of this analysis are illustrated in Figure 5-6, where TNC contour lines for three selected distinct climatic patterns are plotted for HGSHP1 and HGSHP2 configurations (Options 4 and 5 in Section 5.3.2). Sydney is chosen to represent a balanced (temperate) climate, while Hobart and Cairns are chosen to represent heating and cooling dominant climates respectively. In the more balanced climate of Sydney, both the heating and cooling shave factors contribute to the TNC of the system, whereas for the more heating or cooling dominant climates, only one of the shave factors influence the TNC significantly. Only HGSHP1 (RCAC+GSHP system) is considered in Cairns because Cairns requires negligible heating (only 0.4 MWh per year as shown in Figure 5-2). The TNC results for the other 7 cities are also included in the appendix.

The bottom left corners of the contour plots in Figure 5-6 represent a zero shave factor or effectively conventional systems. The top right corners of the plots represent a 100% shave factor or effectively GSHP systems. The points in between represent the calculated TNC considering different shave factor combinations of the HGSHP systems. The lowest TNCs are identified in the plot to indicate the most cost-effective shave factor combinations for HGSHP systems where the system costs the least per unit of thermal energy produced.

In Sydney, the HGSHP1 configuration has the lowest TNC of A\$168/MWh, where the GSHP system is designed to provide 32% peak heating and cooling power demands (Figure 5-6a). In this case, the installed GSHP capacity is 2.3 kW (32% of 7.3 kW). This GSHP able to provide 75% of the annual thermal energy required and the remaining 25% of the year, this GSHP is supported by the conventional system. For the same city, the HGSHP2 configuration has the lowest TNC of A\$185/MWh, where the GSHP system is designed to provide 60% of the peak heating and cooling power demands (Figure 5-6b). For this configuration, 96% of the heating and cooling energy is provided by the GSHP system. It is important to size HGSHP systems for the lowest TNC to maximise the return of investment of the systems for homeowners. For example, the lowest TNC for HGSHP2 is A\$185/MWh, while the TNC for a conventional system comprising a gas furnace and an RCAC system (Option 2) is A\$242/MWh. For this case, incorporating HGHSP2 with the right shave factor combinations can represent a net present value savings of around A\$13,600 over 20 years lifetime of the system. This comes from the TNC differences between the two systems multiplied by total energy needed in Sydney for 20 years lifetime of the system (i.e. $(242-185) \text{ A\$/MWh} \times (5.5 + 6.4) \text{ MWh/year} \times 20 \text{ years}$).

In Hobart, HGSHP1 and HGSHP2 have financially optimum solutions of A\$144/MWh and A\$146/MWh respectively as shown in Figure 5-6c and Figure 5-6d. The analysis suggests that for an HGSHP1 configuration, the optimum HGSHP1 configuration is to provide 24% and 36% of the peak heating and cooling power demands respectively using a GSHP. This configuration can meet 60% of the annual thermal demand in Hobart. The optimum HGSHP2 configuration is to provide 64% and 100% of the heating and cooling peak power demands respectively using a GSHP. This configuration can meet 97% of the annual thermal demand in Hobart.

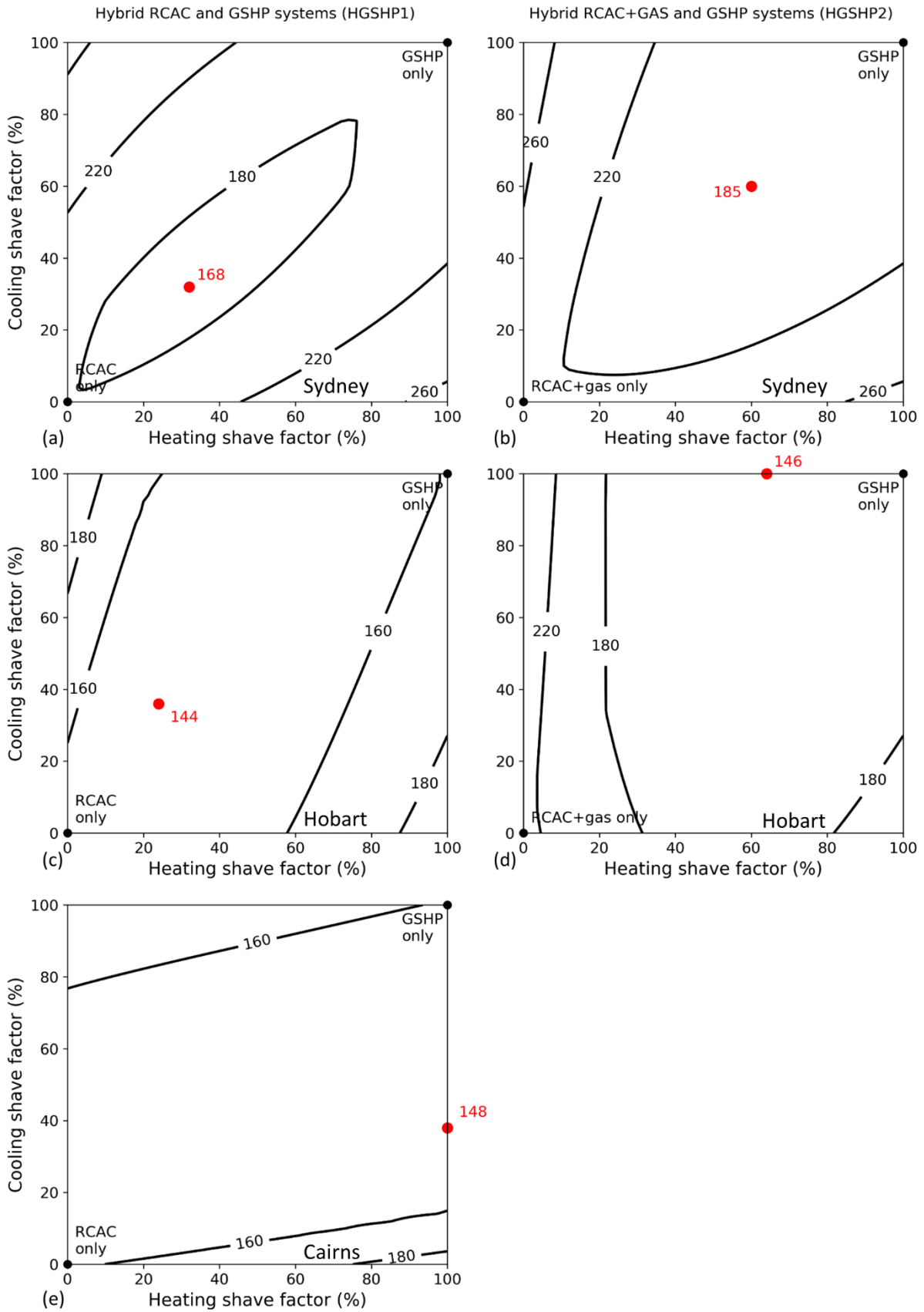


Figure 5-6: TNC in A\$/MWh for (a) HGSH1 and (b) HGSH2 in Sydney, (c) HGSH1 and (d) HGSH2 in Hobart and (e) HGSH1 in Cairns

Figure 5-6e suggests that in Cairns, the lowest TNC is A\$148/MWh at 100% and 38% heating and cooling shave factor. For this configuration, the GSHP system provides 77% of the annual cooling demand. This scenario suggests the advantage of installing an HGSHP system over traditional GSHP system where over three-quarters of the annual thermal demand can be met even though the installed GSHP capacity is just over a third of the peak cooling load. This also results in 120 m reduction in GHE length requirement (down from 270 m) and almost A\$10,000 reduction in capital cost commitment.

The lowest TNC estimations for all ten cities are summarised in Figure 5-7. In this figure, the lowest TNC values for HGSHP1 and HGSHP2 are compared against the lowest TNC values of full GSHP and conventional systems. Furthermore, the TNCs are broken down into the components associated with plant costs, GHE costs and operating costs.

The TNC for GSHP systems varies from A\$117/MWh in Montreal to \$200/MWh in Adelaide. This suggests that the cheapest 1 MWh of sustainable thermal energy can be produced in Montreal. This is mainly due to Montreal's high heating demand (about 48 MWh per year, see Figure 5-2) and their low electricity price, which allows a GSHP system to take advantage of its higher efficiency compared to a conventional system. In contrast, the most expensive unit cost of thermal energy by a GSHP system is in Adelaide, where the high electricity price (31 c/kWh) significantly increases the cost of running a GSHP system.

The TNC of GSHP systems are typically lower than the TNC of an equivalent sized conventional system (RCAC and gas furnace) in all cities, except for Cairns, Montreal and Singapore. These three cities are either highly heating or cooling dominant, which requires very long GHE lengths. This is in line with the NPC comparisons discussed previously in Section 5.4.2.

Adopting HGSHP systems can lower the TNC of GSHP systems in all cities, except in Montreal, where the lowest TNCs would be for the conventional systems. This is presumably the high GHE lengths requirement arising from the high heating dominant climates negating the efficiency of GSHP systems. Thus, conventional systems are preferred to minimise the financial outlay by homeowners who want to cheapest heating and cooling system. The highest savings for implementing HGSHP1 is in Brisbane where HGSHP1 has 12% lower TNC than the GSHP system. Similarly, the highest savings for implementing HGSHP2 is in Melbourne where HGSHP2 has 10% lower TNC than the GSHP system.

Furthermore, when HGSHP systems are compared to their conventional counterparts, an HGSHP1 system can provide a reduction in TNC by up to 14% when it is compared to an RCAC system in Adelaide and an HGSHP2 system can provide a reduction by up to 37% when it is compared to a gas furnace and RCAC system in Hobart.

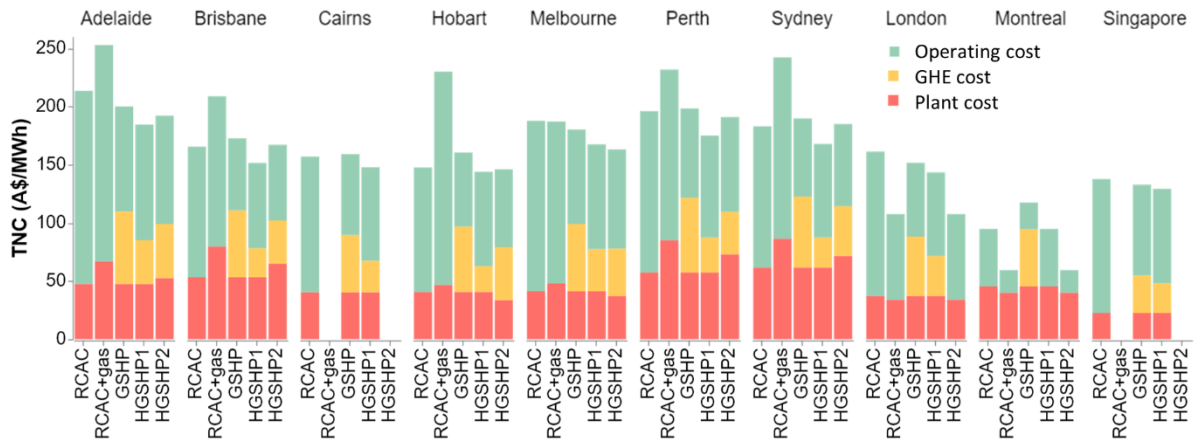


Figure 5-7: Lowest TNC in A\$/MWh comparisons between conventional, GSHP, HGSHP1 and HGSHP2 systems

The results in Figure 5-7 suggest that adopting HGSHP systems instead of GSHP systems can offer up to a 12% reduction in TNCs compared to GSHP systems. This maximum benefit is minor, especially when the challenges of installing two (or three) different heating and cooling systems are considered.

Despite this, HGSHP systems may be a more attractive investment for property owners because these systems generally have shorter GHE lengths and, therefore lower upfront capital costs than GSHP systems while still obtaining advantages over conventional systems. Figure 5-8 presents the initial capital costs required for GSHP and HGSHP systems at the start of a project. Note that these costs do not take account of future replacement costs of any component of the conventional system as part of their respective HGSHP systems. Furthermore, the costs in London, Montreal and Singapore appears to be higher compared to other Australian cities because a bigger capacity machine needs to be installed due to a higher peak heating and cooling load at those locations. In most cases, HGSHP systems have lower initial capital costs. These savings are mainly generated from a reduction in GHE lengths required for each location. In general, more initial cost savings are generated in HGSHP1 systems as only one conventional system needs to be installed compared to two conventional systems in HGSHP2. The adoption of HGSHP1 compared to GSHP systems can reduce capital costs at the start from about A\$15,000 up to about A\$28,000 as an HGSHP1 system requires less GHE lengths compared to GSHP system in each of these locations. For these reasons, even though there may not be a clear financial saving over the full lifetime of the systems, property owners may choose to install HGSHP systems over GSHP systems because of HGSHP systems' lower initial investment cost.

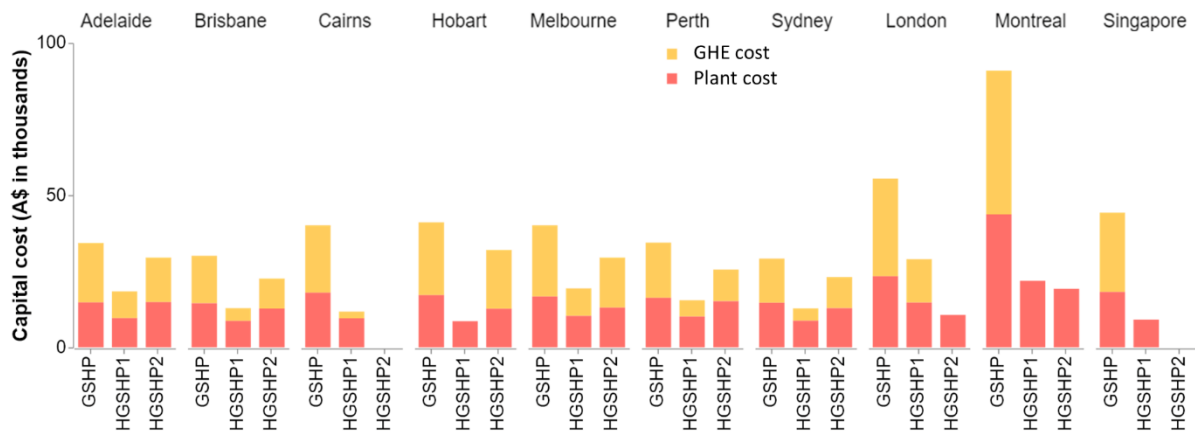


Figure 5-8: Capital costs in A\$ at the start of a construction project (without replacement cost)

5.4.4 Effect of changes in drilling cost for GHEs

The analyses presented in the previous sections were conducted with a drilling cost of A\$80/m, as typically found in Australia (Table 5-4). In this section, the drilling costs are adjusted to A\$50/m, A\$100/m and A\$150/m. The lowest cost reflects costs, for example, in a more competitive and mature GSHP systems industry, while the two highest costs reflect less favourable conditions where, for example, more difficult ground conditions are encountered. The values of all other parameters have been maintained. The effect of a change in drilling cost is investigated for HGSH1 and HGSH2 in the three cities (Sydney, Hobart and Cairns) chosen as before to reflect balanced, heating and cooling dominant climates. The lowest TNC and shave factors for each scenario are presented in Figure 5-9.

In each city, an increase in the drilling cost causes an overall increase in TNCs. The shave factor combinations for the lowest TNC in each scenario shift towards the conventional system (bottom left corner of the plots) as the TNC increases. Tripling the drilling costs from A\$50/m to A\$150/m increases the lowest TNC by A\$55/MWh or less in all cases. The highest TNC increase occurs for HGSH2 in Hobart which is highly heating dominant with a very long GHE requirement. Even at this high drilling price, the GSHP system part of the hybrid component can be sized to provide 52% of the peak thermal load and able to meet 92% of the annual heating requirement since heating by a GSHP system is far more efficient than by a gas furnace.

Furthermore, for this HGSH2 system in Hobart, the heating shave factor (64%) which corresponds to the lowest TNC solution barely changes when the drilling cost is doubled from A\$50/m to A\$100/m (this heating shave factor will decrease only when drilling cost is increased further to A\$150/m). At the same time, the lowest TNC increased by a modest A\$28/MWh or roughly 22% when the drilling cost is doubled from A\$50/m to A\$100/m. This is presumably because an increase in drilling costs is spread out over 20 years' worth of thermal energy. This means that although drilling costs can be relatively high, most of the lifetime costs arise from the operating costs of the system, where local energy price structures and climate play more crucial roles. If the drilling costs become too high relative to other costs, then GSHP or HGSH systems are not financially viable options and property owners should install a conventional system instead as exemplified by the lowest TNCs for HGSH1 systems in most location when drilling price is high.

It may be of interest to consider the data presented in Figure 5-9 in terms of actual dollars. This can be illustrated by considering the effect of the cost of drilling dropping from A\$80/m to A\$50/m in Sydney for an HGSH1 system. For this change, the respective TNCs are A\$168/MWh and A\$156/MWh which represent total costs of A\$39,917 and A\$37,169 respectively for the system over 20 years in Sydney where the annual heating and cooling demand is 11.9 MWh (see Figure 2). The dollar value of a TNC of A\$39,917 for Sydney is arrived at from 168 (A\$/MWh) x 11.9 (MWh/year) x 20 (years). It follows that a savings of about A\$2,000 (or around 5 %) result from this cost change. Such a change could be an advantage as it is an upfront capital cost reduction.

It should be noted Cairns shows an optimum 100% heating shave factor here because there exists a small heating demand (0.4 MWh annually, see Figure 5-2) and almost any GSHP size satisfying part or all of the cooling demand would be able to cater for this small heating demand.

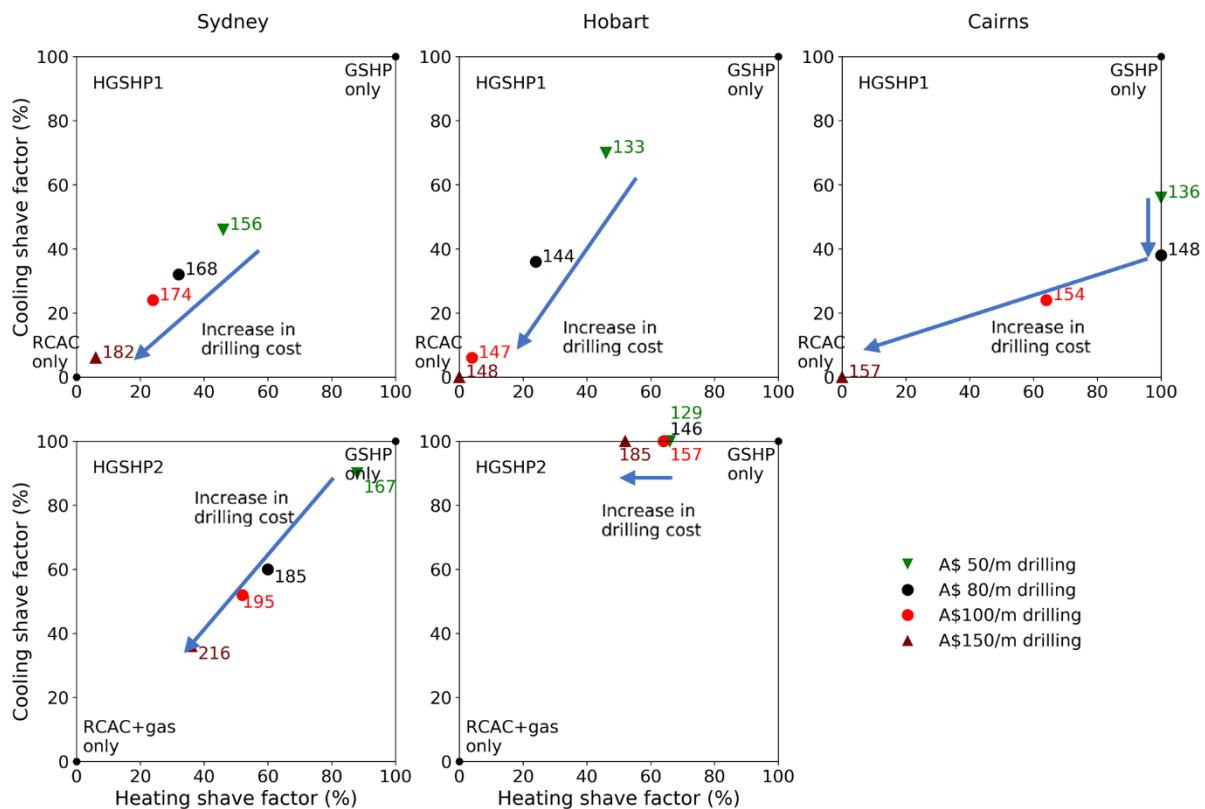


Figure 5-9: Lowest TNC for HGSH1 and HGSH2 systems in A\$/MWh for Sydney, Hobart and Cairns with a drilling cost of A\$50/m, A\$80/m A\$100/m and A\$150/m

5.4.5 Effect of changes in energy prices

The previous sections have shown that the lifetime cost is generally dominated by the operating costs of the various systems (see Figure 5-7). Therefore, the effect of a change in energy prices and their ratios are investigated in this section and compared to current prices and ratios. The first scenario involves doubling both energy prices from the base case, which means the price ratio stays the same. For the second and third scenarios, the price of only electricity or only gas is doubled, hence the electricity to gas price ratio is doubled or halved. The new price parameters and their ratios are presented in Table 5-6. All other parameters used are the same as described in Section 3.3.

Table 5-6: Electricity and gas price considered using different energy price ratio

	Original electricity price (c/kWh)	Original gas price (c/kWh)	Doubled electricity price (c/kWh)	Doubled gas price (c/kWh)	Original electricity / gas price ratio (-)	Electricity / gas price ratio when electricity price is doubled (-)	Electricity / gas price ratio when gas price is doubled (-)
Adelaide	31.3	13.0	62.6	26.0	2.4	4.8	1.2
Brisbane	22.0	10.6	44.0	21.2	2.1	4.2	1.0
Cairns	22.0	10.6	44.0	21.2	2.1	4.2	1.0
Hobart	20.2	12.6	40.4	25.2	1.6	3.2	0.8
Melbourne	27.6	9.4	55.2	18.8	2.9	5.9	1.5
Perth	27.2	10.3	54.4	20.6	2.6	5.3	1.3
Sydney	23.8	12.6	47.6	25.2	1.9	3.8	0.9
London	21.5	4.9	43.0	9.8	4.4	8.8	2.2
Montreal	7.4	1.2	14.8	2.4	6.2	12.3	3.1
Singapore	20.3	16.8	40.6	33.6	1.2	2.4	0.6

Note: price shown for international cities are in A\$ equivalent

Figure 5-10 presents the lowest TNC for HGSH1 and HGSH2 for Sydney, Hobart and Cairns when both energy prices are doubled. HGSH2 system is not considered for Cairns due to its minimum annual heating requirements.

Doubling both energy prices cause a significant increase in TNCs in all cities. At the same time, the optimum shave factor shifts towards the top right corner of the plot which represents a traditional GSHP system. This means that the new pricing takes greater advantage of the higher GSHP system efficiency. There is practically no change regarding the optimum shave factors for HGSH2 system in Hobart when both energy prices are doubled because, at this hybrid proportion, the GSHP system has already provided 98% of the annual energy requirements. Hence, an increase in energy price will only increase the TNC.

For the second and third scenarios, the lowest TNCs for HGSH2 systems when either price is changed are presented in Figure 5-11. Increasing either price for HGSH1 is not discussed here since these systems only use electricity as an input and the result of this analysis has been presented in the top half of Figure 5-10.

In Sydney, doubling only the electricity price results in a shift towards the bottom left corner of the plot, towards a full conventional system as shown in Figure 5-11. Doubling only the electricity price increases the energy price ratio to 3.8, where it is more cost-effective to provide a larger portion of the heating demand by gas instead of electricity. Note that the effect of doubling just the electricity price is different with and without the presence of gas as a fuel source. With gas as a substitute option in HGSH2, the use of an HGSH2 system with a higher gas proportion as shown in Figure

5-11 is more effective. In contrast, without gas as a substitute option in HGSH1, the use of a more efficient GSHP system as presented in Figure 5-10 is more effective. Note that when only the gas price is doubled, the TNC increases slightly to 187 A\$/MWh. However, at this shave factor combination, the GSHP provides almost 99% of the annual energy requirement in Sydney.

The substitution effect described above also applies to the case in Hobart. Doubling the electricity price in Hobart resulting GSHP system to be preferred when gas is not available as a substitute (Figure 5-10), but when gas is available, then conventional systems is preferred (Figure 5-11). Doubling only the gas price in Hobart results in minimum changes compared to the base case, both in terms of the shave factors mix and the lifetime TNCs.

Doubling only the gas price in Cairns is not considered since cooling is practically irrelevant over there.

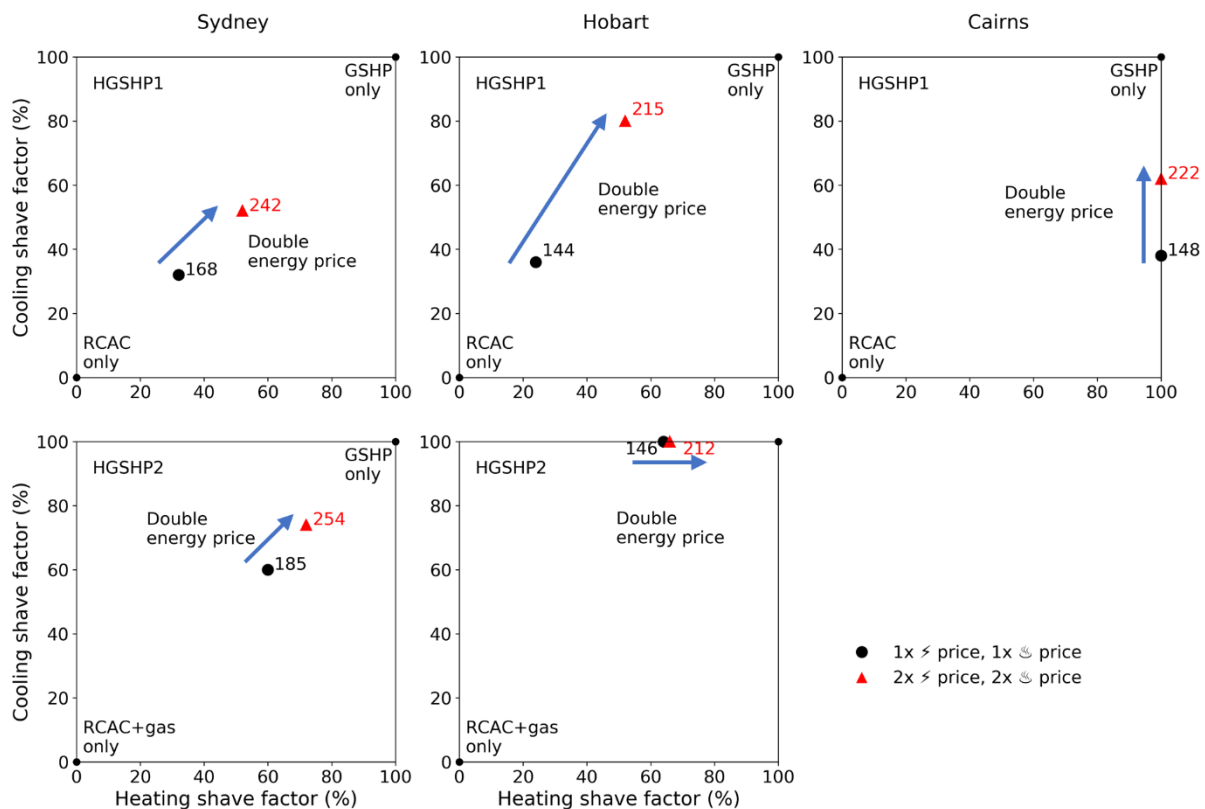


Figure 5-10: Lowest TNC for HGSH1 and HGSH2 systems in A\$/MWh for Adelaide, Hobart and Cairns when both electricity and gas prices are doubled

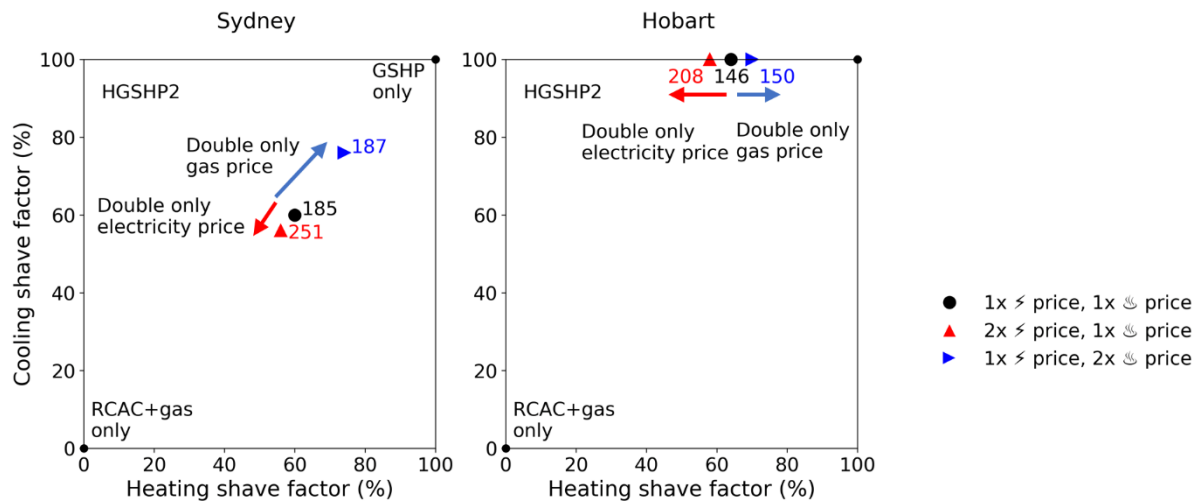


Figure 5-11: Lowest TNC for HGSH2 systems in A\$/MWh for Adelaide, Hobart and Cairns when one of the electricity or gas price is doubled

5.4.6 Effect of changes in thermal conductivity of the ground

The analyses in the previous sections assumed a ground thermal conductivity (λ) of 2.5 W/m.K. This value represents the thermal conductivity of a rock formation, such as the Silurian mudstone typically found under much of Melbourne [126] or thermal conductivity of saturated sand [163]. This value may not be typical of the ground thermal conductivity found elsewhere and this can affect the costs comparisons made. For this reason, different ground thermal conductivities ranging from 0.7 W/m.K to 2.5 W/m.K are investigated in this section. These values have been chosen to represent typical soils such as sand, silt and clay; both in saturated and unsaturated conditions as measured by Bose [163]. For simplicity, the analyses are conducted using the base case cost parameters presented in Table 5-4 and Table 5-5. It is also important to recognise that the influence of groundwater flow (and convection) is ignored in this work for simplicity.

A decrease in ground thermal conductivity must cause an increase in GHE length. Hence, as is shown in Figure 5-12, the lowest TNC for each location increases as thermal conductivity decreases. Further, as the ground thermal conductivity decreases, the locations of the lowest shave factor combinations shift towards the bottom left corner of the plots, i.e.: towards conventional systems. This increase in the GHE length reduces the benefit of more efficient GSHP or HGSH2 systems and at some point, conventional systems become the better cost options. For this reason, the thermal conductivity of the ground should be carefully investigated as this may have a significant effect on the viability of GSHP and/or HGSH2 systems.

An exception to this is for the HGSH2 case in Hobart, where a significant decrease in ground thermal conductivities resulting in a slight decrease in heating shave factors from 64% to 44%. This is because the lifetime costs for the less efficient gas furnace option is much more significant compared to the increase in the GHE installation costs if the system is installed in an area of low ground thermal conductivity. This observation is similar to the earlier analysis for HGSH2 systems (Figure 5-9) when drilling costs were significantly increased.

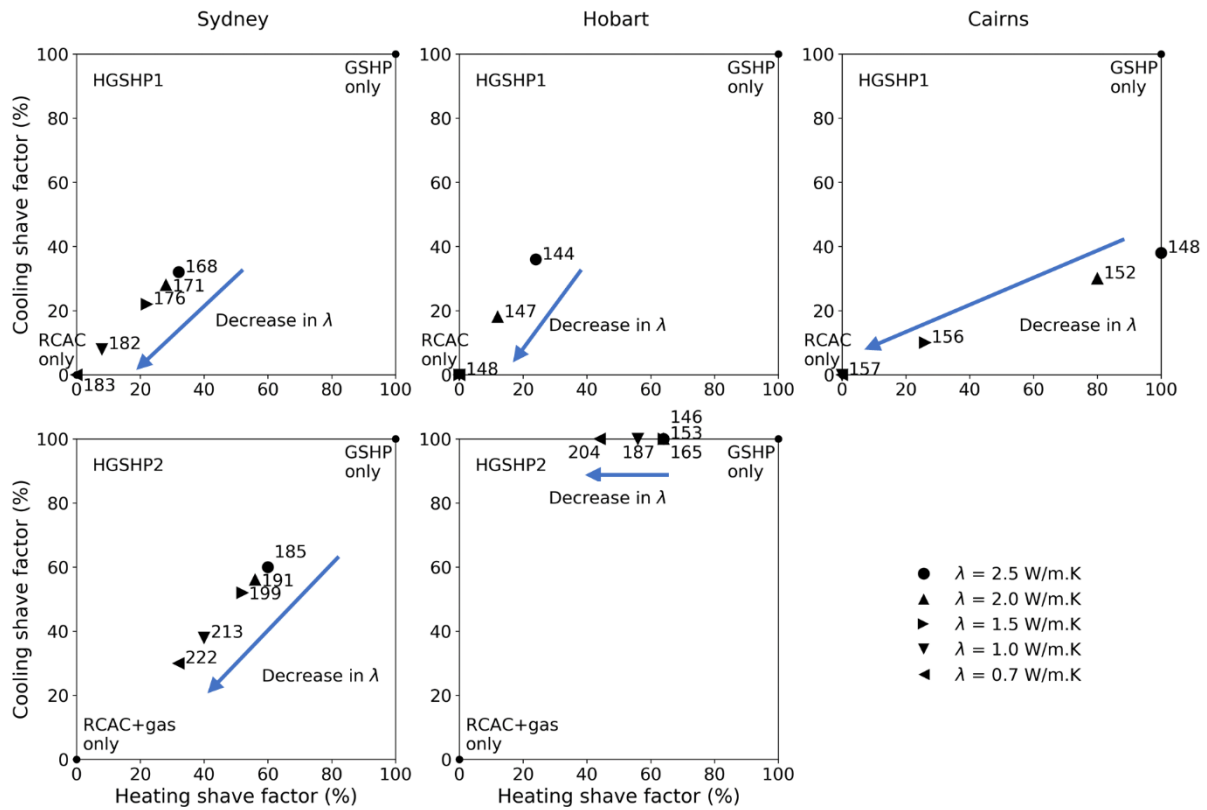


Figure 5-12: Lowest TNC for HGSH1 and HGSH2 systems in A\$/MWh for Sydney, Hobart and Cairns as ground thermal conductivity (λ) decreases

5.4.7 Effect of changes in CoPs of RCAC and GSHP systems

One of the most important parameters used in the above cost comparison is the CoP values of the RCAC and GSHP systems. The CoPs of the chosen equipment directly affects the operational costs and later on, the lifetime costs and TNC of the relevant systems. Replacing the chosen heat pumps with a higher or lower efficient heat pump may change the results of the analysis conducted here. This is explored in this section, where the CoP performance curve from the manufacturer's specification was adjusted by increasing and decreasing the CoP curve by 0.5. This effectively adjusted the SCoP, where for example in Sydney, the SCoP of the RCAC becomes 2.6 ± 0.5 and GSHP becomes 4.7 ± 0.5 . For simplicity, the efficiency of a gas furnace is kept the same (0.9) as this value depends on the combustion rate of gas.

Figure 5-13 presents the results when the assumed CoP for RCAC systems is adjusted while keeping the GSHP CoP at the initial values for both HGSH1 and HGSH2 systems for Sydney, Hobart and Cairns. In general, as the CoP of the RCAC system is increased, the lowest TNC in each location decreases. An increase in RCAC CoP means that this system is more efficient, hence less electrical energy is needed to provide the same amount of heating and cooling, which in turn decreases the lifetime cost to operate the system and lower overall TNCs. As the RCAC becomes more efficient, then the lowest shave factor combinations shift towards the bottom left corner of the plots, i.e.: towards conventional systems.

From Figure 5-13, it becomes apparent that HGSH1 system is more sensitive to changes in the CoP of the RCAC system than in HGSH2 system. In HGSH1 system, both GSHP and RCAC systems are powered by electricity, which means the operational costs are determined by the relative efficiency between both systems. This is in contrast to HGSH2 system where the heating can be provided by a gas furnace. Since both Sydney and Hobart are heating dominant, then a change in the CoP of the RCAC system has a limited effect in the TNC of HGSH2 system since the RCAC only provides cooling. This can be observed in Figure 5-13, where there is practically no changes in TNC for the HGSH2 system in Sydney and Hobart when the CoP of the RCAC system was increased. This can be observed in Figure 5-13, where there is practically no changes in TNC for the HGSH2 system in Sydney and Hobart when the CoP of the RCAC system was increased.

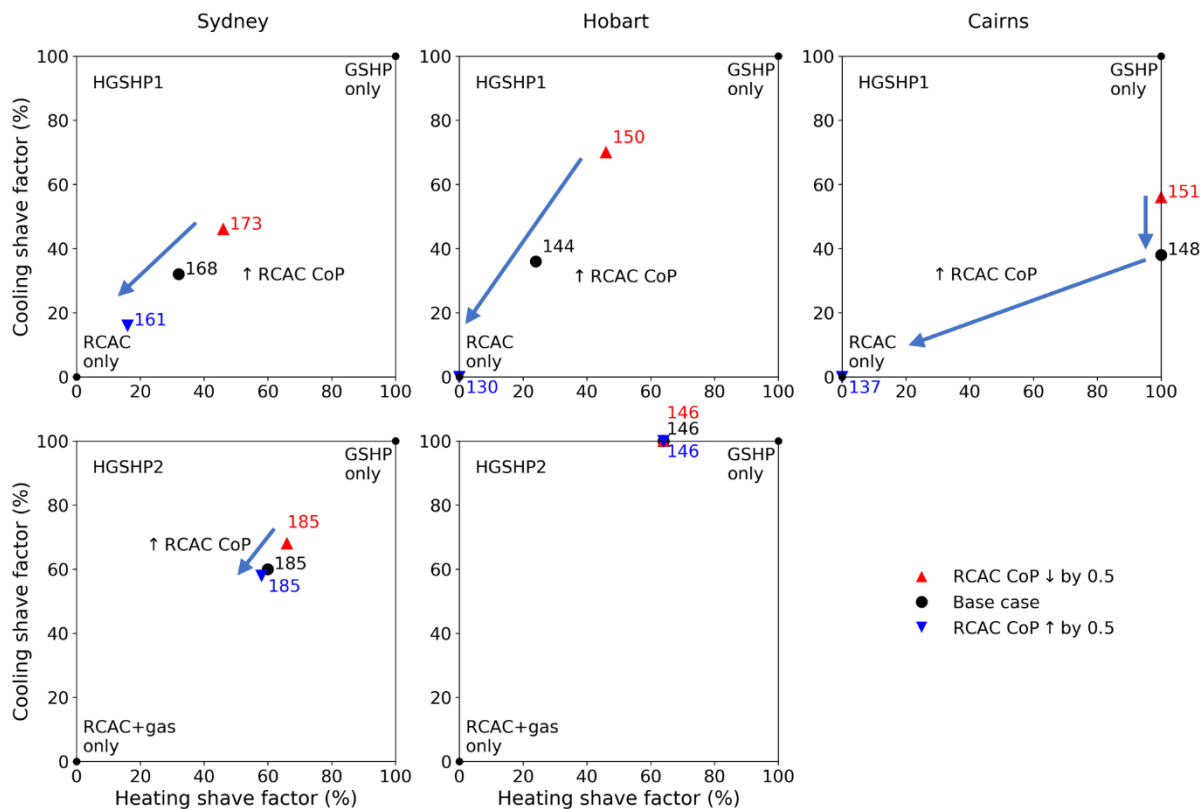


Figure 5-13: Lowest TNC for HGSH1 and HGSH2 systems in A\$/MWh for Sydney, Hobart and Cairns as CoP of RCAC system increases

Similar results can be observed in Figure 5-14 where the CoP of a GSHP system is changed while the CoP of the RCAC system is held constant. An increase in the CoP of the GSHP system causes a decrease in TNC and generally the lowest shave factor combination shifts towards the top right corner of the plots towards the GSHP system.

It is interesting to note that for the HGSH2 system in Hobart, a high heating shave factor is still preferred even when the CoP of GSHP system is reduced by 0.5 (resulting SCoP of GSHP system in Hobart around 3.6). At this point, the lowest TNC and heating shave factor proportion is still the same as the base case, at 64% heating shave factor. Further investigation reveals that the efficiency ratio between heating by GSHP and gas system is 4 (GSHP's SCoP of 3.6 / gas efficiency 0.9). This value is much higher compared to the electricity to gas price ratio of 1.6 in Hobart (see Table 5-6). Both of these parameters suggest that heating by GSHP system is far more effective than a gas system, but the price of electricity is only slightly more expensive than gas, hence heating by GSHP system is far more desirable. If this gap between the price and efficiency ratio is narrowed, it is expected that a higher proportion of conventional system would be preferred when the CoP of GSHP system is decreased.

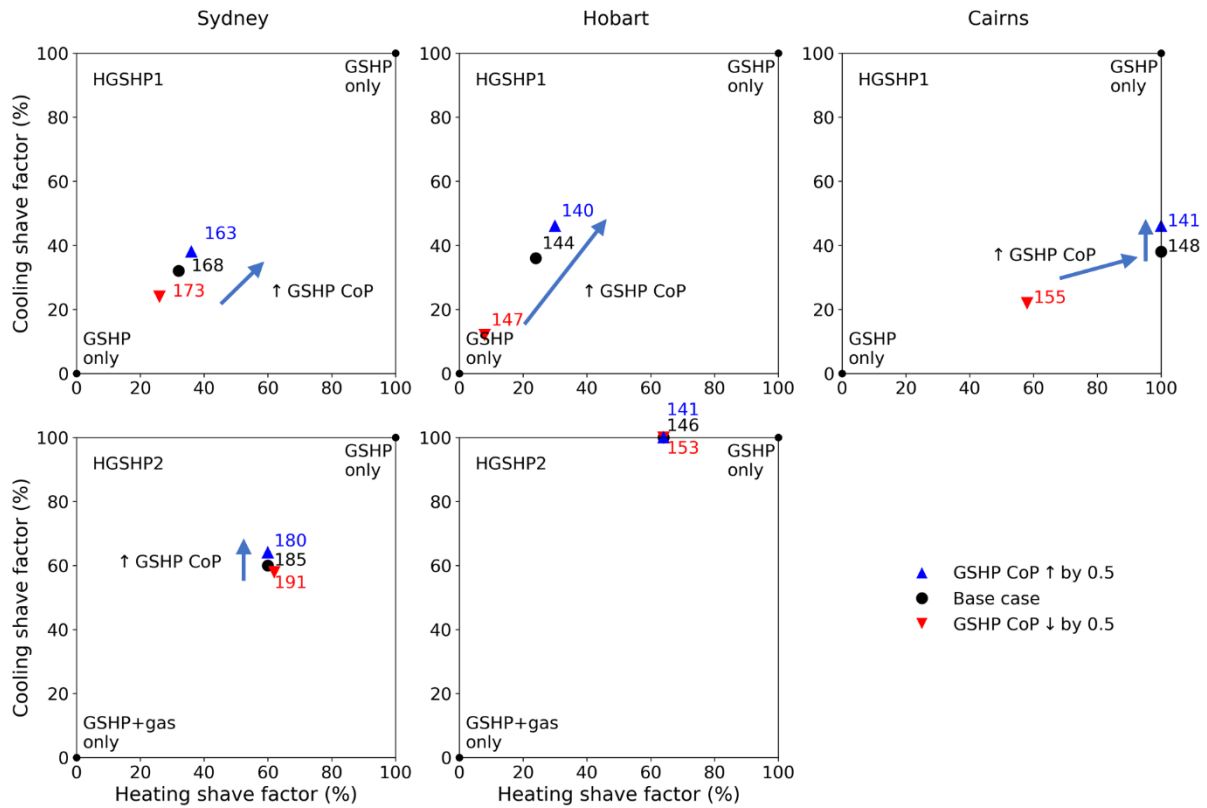


Figure 5-14: Lowest TNC for HGSH1 and HGSH2 systems in A\$/MWh for Sydney, Hobart and Cairns as CoP of GSHP system increases

5.5 Conclusions

Ground Source Heat Pump (GSHP) systems are energy efficient space heating and cooling systems that usually have considerably higher annual average coefficients of performance (CoP)s, lower carbon emissions, but usually higher capital costs than conventional systems. However, this is not always the case because the financial performance of GSHP systems depends on many parameters including climatic conditions, ground conditions, the efficiency of the alternative heating and cooling systems, drilling prices and prices of electricity and gas in the regions where the systems are installed. These factors have to be considered when cost comparisons of systems are made.

To maximise financial benefits, hybrid ground source heat pump (HGSH) systems, a combination of GSHPs and traditional systems have been proposed as economical heating and cooling options.

This chapter compares the costs of GSHP, HGSH and conventional heating and cooling systems under different climatic, geological conditions, installation and energy price structures exemplified in seven cities across Australia and three other cities worldwide. The comparison of financial indicators of the heating and cooling options considered suggests that when HGSH systems are sized to maximise their financial benefits, the hybrids typically have lower total normalised costs (TNCs – net present costs per thermal energy unit) than GSHP or conventional systems.

The benefit of hybrid systems over GSHP systems can increase or decrease depending on the cost of the variables involved. Increased drilling costs result in a marginal increase in TNCs and as the cost increases, it may be more cost effective to use conventional systems instead. However, this is not always the case as demonstrated in the highly heating dominant climate of Hobart where a gas furnace may be a heating alternative. In this case, even with a tripled drilling cost, the most cost efficient heating and cooling system is a hybrid system, but the GSHP system component effectively providing most of the heating needs. However, if the heating and cooling are provided by an RCAC system then a tripling of drilling costs can improve the attractiveness of a conventional system.

GSHP systems are more attractive when both gas and electricity energy prices are increased at the same rate. However, the effect when prices vary at different rates is more complicated and needs to be investigated case by case. Both GSHP and HGSHP systems are also less cost attractive when installed at locations with relatively low ground thermal conductivity. Furthermore, the efficiency of the heating and cooling system can greatly affect which systems to install. Typically, the lifetime costs are dominated by the operating costs of a system. Therefore, installing a greater proportion of the most efficient system typically leads to the highest financial return.

The sensitivity analysis presented here suggests that the operational cost dominates the lifetime costs. This is shown where changes in factors that may affect operational costs such as the energy prices and the efficiency of both GSHP and RCAC systems have a more significant effect on the lifetime costs of the systems, when compared to changes in factors that may affect capital costs such as the drilling costs and thermal conductivity of where the system is installed at.

The study demonstrates that the sizing of HGSHP systems can be a complex procedure which depends on the design objectives, as well as climatic conditions and various other factors which need to be considered. A factor which has not been included in the above assessments is the financial effect of environmental factors such as a reduction in carbon emissions and the financial incentives that are on offer in various countries. These factors will be considered in future work.

6 Environmental assessment of hybrid ground source heat pump systems

6.1 Overview and structure

This chapter extends the work conducted in Chapter 5. The aim of this chapter was to present a design framework to consider both economic and environmental benefits of HGSHP systems in comparison to the GSHP and conventional systems. A Pareto optimum approach was undertaken to provide a solution set that accounts for both lifetime costs and emissions. Overall, this chapter may provide a basis on which decisions about whether to install an HGSHP system with the objective to minimise their lifetime costs or emissions. A solution which considers both factors with equal weight is also provided herein.

A paper titled “Environmental assessment of hybrid ground source heat pump systems” based on this chapter has been published in the journal *Geothermics*. However, to maintain consistency with thesis the full text of the paper is presented here. This chapter and publication are the author’s original work. Co-author authorisation forms have been included in this submission.

6.2 Introduction

Worldwide energy use is expected to rise due to an increase in population and global warming. In Australia, electricity is the most dominant energy source used for space heating and cooling, where 38% of households use electric heaters and 49% use reverse cycle air conditioners (RCACs) for cooling [1]. The associated carbon emissions are exacerbated by the fact that 60% of Australian electricity generated in 2018 was from coal [3]. Not surprisingly, it was reported that the electricity sector is the biggest polluter, representing 33% of the carbon emissions in Australia [4]. A global analysis paper by Ang and Su [5] reported that in 2013, Australia was the fifth most carbon-intensive electricity producer in the world, with an electricity emission factor of 0.7806 kgCO₂e/kWh of electricity used. In comparison, Ang and Su [5] estimated a worldwide average of 0.52 kgCO₂e/kWh, which means that compared to the worldwide average, there is an additional 50% carbon emissions for each kWh of electricity used in Australia.

This electricity consumption should be reduced to achieve long-term environmental sustainability and also to meet Australia’s commitment at the Paris Climate Change Conference to reduce GHG emission by around 150 Mt CO₂e by 2030 [164]. Furthermore, it has been reported that emission abatement in the electricity sector is more cost-efficient compared to reducing emissions in other sectors [4]. One way to reduce this electricity consumption worldwide is by using more efficient heating and cooling systems, such as ground source heat pump (GSHP) systems.

Research on GSHP systems has increased in recent years and details about the systems can be found elsewhere [11, 19, 143]. Efficiency or coefficient of performance (CoP) of GSHP systems have been studied experimentally, analytically and numerically [16-18, 25, 128], and GSHP systems are typically more efficient than conventional systems [17, 25, 26, 165]. A system with a higher CoP means that less electrical energy is required to run the system. Hence, the adoption of GSHP systems instead of conventional systems can contribute to the objective to reduce greenhouse gas (GHG) emissions.

Despite all these, the uptake for GSHP systems has been relatively limited, with factors such as finance, technology and policy having been cited as the typical barriers to adopt this technology [27].

Several authors have indicated that installation cost is the most difficult challenge to overcome [27, 41]. Design methods such as hybrid GSHP (HGSHP) systems have been suggested, where the lifetime costs are minimised by taking advantage of both the lower capital costs of conventional systems and the lower operational costs of GSHP systems [14, 97-99, 166, 167]. However, this hybrid system solution with the lowest lifetime costs is usually not the most optimal from the environmental perspective. GSHP systems are typically the most efficient, hence they are expected to emit the least emission compared to other heating and cooling systems.

The environmental impact of GSHP systems during the operational stage has been investigated previously. The use of GSHP and HGSHP systems has been reported to reduce GHG emissions in Ontario, Canada [168]. Other authors estimated that a 35% reduction in GHG emissions is possible in Sweden and Switzerland [169, 170]. Literature survey reveals that the life cycle assessment (LCA) method is one that is most commonly used, where environmental impact is considered throughout the life cycle of the system [21, 47, 88, 171, 172]. The LCA method considers the lifetime environmental impact from the resources needed for the raw materials, assembly, transport, operation and disposal.

These previous works suggest that HGSHP systems have the potential to be beneficial financially and environmentally. There is also some trade-off between financial and environmental savings between the users who pay the financial costs and society who usually bear the environmental costs. Hence, a multi-objective optimisation strategy is needed, where an optimal hybrid system configuration is proposed while considering both financial and environmental benefits.

This chapter built on previous work by Aditya et al. [14], where it was reported that HGSHP systems have the potential to reduce lifetime costs in Australia. In this chapter, a multi-objective optimisation method is adopted where the economic and environmental performance of HGSHP systems are investigated under Australian climatic, cost and emission conditions. Based on these design parameters, a Pareto optimal approach is then utilised to find the optimum solution set that considers both financial and environmental benefits of HGSHP systems. Finally, a sensitivity analysis is conducted to investigate the impact of potential changes in those key design parameters.

6.3 Data and methodology

Seven major Australian cities have been chosen to represent the different climatic conditions encountered in Australia, ranging from temperate to tropical climate [173]. Those cities are Adelaide, Brisbane, Cairns, Hobart, Melbourne, Perth and Sydney.

6.3.1 Thermal loads

The peak thermal load and hourly thermal demand at each city were simulated by using EnergyPlus [148] for a typical 150 m² Australian residential dwelling. The parameters used for this simulation is provided in Table 6-1. For simplicity, the same building is assumed for each location. However, the climatic condition at each location is different, resulting in the buildings to have different peak heating and cooling loads as well as annual thermal demands. The undisturbed ground temperature (T_g) at shallow depth (less than 200 m) can be assumed as the average local air temperature plus 2 °C, as described in IGSHPA [10]. The resulting thermal load, total annual energy demand and undisturbed ground temperature in each of the Australian cities are summarised in Table 6-2.

Table 6-1: Description of the case study building including parameters used for EnergyPlus simulation

Building characteristics	Value	Note
Building floor area (m ²)	150	1 living room, 2 bedrooms
Floor height (m)	3	
Number of occupants	4	
External wall U-value (W/m ² K)	0.987	Concrete wall & gypsum, including insulation
External roof U-value (W/m ² K)	0.285	Metal decking, including insulation. Flat roof
External window U-value (W/m ² K)	6.424	Glass window
Zone ventilation (air change per hour)	1	20% more than the minimum outdoor area required in Australia (0.35 L/s/m ²), AS 1668.2-2012 [151]
Indoor heating thermostat set point (°C)	20	
Indoor cooling thermostat set point (°C)	22	
Occupancy		Assume all year around
Weather data		TMY file available at each location from Meteonorm [146]

6.3.2 Heating and cooling options

The previous survey by the Australian Bureau of Statistics [1] indicated that 38% and 30% of households in Australia use electricity and gas, respectively, for their heating requirements, while for cooling, 49% of households use electricity. Due to both heating and cooling requirements, Australians tend to use a reverse cycle air conditioner (RCAC) to satisfy heating and cooling with a single system. Therefore, five heating and cooling options are considered in this chapter:

1. Heating and cooling by an RCAC;
2. Heating with a gas furnace and cooling by an RCAC;
3. Heating and cooling with a GSHP;
4. Heating and cooling by an HGSH system (HGSH1) with a GSHP and an RCAC;
5. Heating and cooling by an HGSH system (HGSH2) with a GSHP, a gas furnace for heating and an RCAC for cooling.

The CoPs of GSHP and RCAC system typically vary throughout the year. The entering water temperature (EWT) to the GSHP determines its CoP, while the CoP of RCAC system is affected by the outside air temperature. Hence, both systems are expected to have different CoP due to the differences in climatic conditions in each city. In this case study, a high-performance GSHP (Water Furnace NSKW06) and RCAC unit (Fujitsu AOTG30KMTA) were selected. Those units are available off the shelf and the manufacturers provided a detailed datasheet which was utilised to compute the hourly CoPs of both systems. The hourly CoP of the GSHP system was calculated by using a methodology from Weeratunge et al. [96], where the hourly ground temperature and EWT were simulated and used to determine the hourly CoPs at each location. The hourly CoP of the RCAC system was much simpler to compute as they are only dependent on the outside air temperature at each location. Table 6-2 indicates these CoP variation between each city where the hourly CoPs are averaged and referred as a seasonal CoP (SCoP). The efficiency of a gas furnace is assumed as a constant 0.9 for simplicity as this value represents a constant rate of gas combustion.

Table 6-2: Ground temperatures, peak heating and cooling loads, average seasonal CoP of RCAC and GSHP system

	Estimated average T _g at shallow depth (°C)	Estimated peak heating/cooling load (kW)	Annual heating/cooling demand (kWh)	SCoP of RCAC (-)	SCoP of GSHP (-)
Adelaide	18.7	7.4/6.7	12.5/3.2	2.5	4.6
Brisbane	22.2	7.2/7.2	5.3/8.3	2.6	4.7
Cairns	26.5	3.3/9.0	0.4/22.0	2.5	4.2
Hobart	12.9	8.6/5.6	20.7/0.6	2.5	4.2
Melbourne	16.5	8.4/5.5	18.2/2.0	2.5	4.5
Perth	19.9	7.8/8.1	8.8/5.3	2.6	4.7
Sydney	20.1	5.8/7.3	6.4/5.5	2.6	4.7

The design length (L_{GHE}) for the ground heat exchanger (GHE) is calculated based on the ASHRAE design approach shown in Equation (12) [60], with the design parameters defined in Table 6-3.

$$L_{GHE} = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_c R_{6h}}{\frac{(T_i + T_o)}{2} - (T_g + T_p)} \quad (12)$$

where each factor is defined in the list in Table 6-3. It is important to recognise that geological parameters such as ground thermal conductivity (λ) can vary across the cities considered here. For the base case, 2.5 W/m.K is assumed as the base λ , but this value is varied in Section 6.4.3 for a sensitivity analysis.

The HGSHP systems here consider the proportion of heating and cooling loads provided by GSHP and conventional systems. This proportion is referred to as the *shave factor*. In this work, the heating and cooling shave factors are varied from 0% to 100% with a step size of 2% to cover a range of configurations. The 0% shave factors refer to conventional systems, while 100% shave factors refer to GSHP systems. The shave factors between 0% and 100% represent hybrid systems combination of both RCAC and GSHP systems. A shave factor of 60% means the GSHP system provides 60% of the peak load, while the conventional system provides the remaining 40%.

Table 6-3: Parameters used for sizing of GHEs

Design parameter (units)	Description	Value
q_h, q_m, q_y (kW)	Peak hourly, monthly average and yearly average ground loads	Calculated based on building thermal demand, heating and cooling shave factors, and COP of GSHP
R_b (m.K/W)	Effective thermal resistance of the borehole	0.103
λ (W/m.K)	Ground thermal conductivity, used to calculate R_{6h} , R_{1m} and R_{10y}	2.5
R_{6h} (m.K/W)	Effective thermal resistance of the ground to 6 hours of ground load	0.106
R_{1m} (m.K/W)	Effective thermal resistance of the ground to 1 month of ground load	0.146
R_{10y} (m.K/W)	Effective thermal resistance of the ground to 10 years of ground load	0.153
T _g (°C)	Undisturbed ground temperature at shallow depths	Listed in Table 2
T _{i,h} (°C)	EWT to GSHP in heating operation	T _g - 5.5 °C (T _g - 10 °F)
T _{i,c} (°C)	EWT to GSHP in cooling operation	T _g + 11.1 °C (T _g + 20 °F)
T _p (°C)	Temperature penalty	0 (GHE is thermally independent)

6.3.3 Cost and emission parameters

In this chapter, life cycle analysis is used to compare the total lifetime costs and emissions of all the heating and cooling systems. All the systems are assumed to be installed and used for 20 years. It is further assumed that a GSHP has a lifespan of 20 years while an RCAC and a gas furnace each have a lifespan of 10 years, based on Lu et al. [41]. This means that after 10 years, a new RCAC and gas furnace need to be installed to replace the old one, which incurs additional capital costs and GHG emissions. All the analysis is in Australian dollars (A\$), where currently one A\$ is US\$ 0.72.

The net present cost method is selected as the principal economic indicator for all the heating and cooling systems considered. The NPC can be calculated using Equation (13):

$$NPC = \sum_{t=1}^{20} \frac{C_t}{(1+r)^t} \quad (13)$$

where C_t represents the cash outflow at time t in years, which can be a capital cost or an operating cost. This cost at time t will be discounted back at interest rate r (3.5%, see Table 6-4) over a 20-year design life of the system. The capital costs include the cost to install the systems at the start and, if necessary, the cost to replace the systems at the 10-year mark. For GSHP and HGSHP systems, there is also an initial cost to install the GHEs. The operational costs are simply the cost to operate the systems for 20 years. All assumed parameters for cost calculations are presented in Table 6-4, while the unit prices for electricity and gas are presented in Table 6-5, based on various major local energy retailers [141, 153, 154].

A similar life cycle method is considered for the environmental assessment in this chapter. Initial activities such as manufacturing, transport and installation processes can cause some GHG emissions. Work by others has indicated that these initial emissions (IE) are relatively low compared to the lifetime GHG emissions (LGE) generated through the operational emissions (OE) stage of the heating and cooling systems [47, 171]. We hypothesise that these IE would be a small percentage compared to the LGE as the electricity emission factor in Australia is quite high. Nevertheless, we include these IE in the analysis for completeness, including additional IE required when RCAC or gas system is replaced at the 10-year mark. The LGE in each city can be calculated using Equation (14).

$$LGE = IE + \sum_{t=1}^{20} OE_t \quad (14)$$

where IE [$kgCO_2e$] is the sum of the initial emissions for drilling and the initial emission of the relevant equipment (GSHP or gas furnace or RCAC), using the parameter outlined in Table 6-4. OE [$kgCO_2e$] is the annual operational emissions, which is the calculated annual emissions [kWh] multiplied by the emission factor [$kgCO_2e/kWh$] for electricity or gas. The emission factors used for this calculation is outlined in Table 6-5.

It is important to recognise that the electricity emission factor is different in each city, with Hobart having the cleanest electricity (0.14 $kgCO_2e/kWh$), where most of the electricity is generated by a renewable source such as hydro. In contrast, the highest emission-intensive electricity is in Melbourne (1.08 $kg CO_2e/kWh$), where most of the electricity is generated from brown coal. There is only one emission factor value for gas as the value is based on the emissions generated from gas

combustion as opposed to several emission factors for electricity in each Australian state as the value depends on the combustion generated from a distinct fuel (coal, gas, renewable etc) mix.

Based on using the above parameters, the NPC and LGE for all of the heating and cooling systems can then be calculated for each heating and cooling shave factor combination for the seven cities considered in this study.

Table 6-4: Parameters assumed for cost comparisons (based on Lu [47])

Parameter (units)	Value	Note
Cost of drilling (A\$/m)	80	Borehole installation
Cost of GSHP (A\$/kW)	2,000	Equipment and installation of the system
Cost of gas furnace (A\$/kW)	500	Equipment and installation of the system
Cost of RCAC (A\$/kW)	1,000	Equipment and installation of the system
Emissions for drilling (kgCO ₂ e/m)	7.8	Including HDPE pipes, drilling and grouting
Emissions for GSHP (kgCO ₂ e/kW)	69	Including material and manufacturing
Emissions for gas furnace (kgCO ₂ e/kW)	1.4	Including material and manufacturing
Emissions for RCAC (kgCO ₂ e/kW)	69	Including material and manufacturing
Electricity inflation rate (%)	6.2	
Gas inflation rate (%)	6.14	
Discount rate, r (%)	3.5	
Lifespan of GSHP system (years)	20	
Lifespan of gas furnace and of RCAC (years)	10	
Replacement of gas furnace and RCAC	Every 10 years	
Design life (years)	20	

Table 6-5: Price and unit emission factors for electricity and gas for all the cities considered

	Electricity price (c/kWh)	Gas price (c/kWh)	Electricity/gas price ratio (-)	Electricity emission factor (kgCO ₂ e/kWh)	Gas emission factor (kgCO ₂ e/kWh)	Electricity/gas emission ratio (-)
Adelaide	31.3	13.0	2.4	0.49		2.65
Brisbane	22.0	10.6	2.1	0.79		4.27
Cairns	22.0	10.6	2.1	0.79		4.27
Hobart	20.2	12.6	1.6	0.14	0.185	0.76
Melbourne	27.6	9.4	2.9	1.08		5.83
Perth	27.2	10.3	2.6	0.70		3.78
Sydney	23.8	12.6	1.9	0.83		4.49

6.3.4 Pareto optimal approach

The Pareto optimal approach was originally developed in the economics field [174], but it has been extended into other areas, including GSHP systems design [15, 175-177]. Marler and Arora [178] suggested that for a multi-objective optimisation method, there may not be a single global solution and a solution set may be required. In this chapter, the design process for HGSHS systems considers both NPC and LGE for different heating and cooling shave factor combinations.

The solution set that is considered as the *Pareto optimal* is the set such that there does not exist another shave factor combination with lower NPC or LGE. For example, each point in Figure 6-1 represents the NPCs and LGEs for all shave factor combinations for HGSHS1 in Sydney. The thicker black line represents the Pareto optimum solution set, where points A and C are included in the solution set. Point B is not Pareto optimal as there exist other possible shave factor combinations with lower NPC and the same LGE as point B (such as point A) and there exist other possible shave factor combinations with lower LGE and the same NPC of point B (such as point C). Therefore, it is

considered generally efficient to size GSHP systems at any point along this Pareto optimum solution to minimise both NPC and LGE.

It should be noted that point A is considered as the solution with the lowest NPC, while point C is considered the solution with the lowest LGE. It is understandable that most homeowners would choose to design their HGSHP systems at point A with the lowest lifetime costs to install and operate the heating and cooling system. In contrast, the government (and society) might want to encourage homeowners to minimise their LGE by choosing point C. This mismatched incentive creates a financial and emission gap between point A and point C. Depending on their environmental objectives, the government can overcome this NPC gap (or part of it) by providing various financial incentives, such as through carbon taxes, green incentives or tax breaks for going green. These incentives can potentially encourage homeowners to move away from point A (along the Pareto optimum solution) to reduce their lifetime GHG emissions.

The single most optimum point from this solution set, however, will need to be decided by the relevant stakeholders given the weighted importance of NPCs and LGEs. This single point is based on a range of factors and most likely is unique for each location and scenario. One method about how to decide this point is presented by Sayyaadi et al. [176] and Huang et al. [15], who have suggested an equal-weighted coefficient to find a single optimum point from a Pareto solution set. This optimum point was suggested as the point that is mathematically defined as the 'elbow of the curve' or the point with the maximum curvature. Satopaa et al. [179] presented an algorithm to find this optimum point (point D in Figure 6-1), where this is the point with the longest perpendicular distance to the straight-line AC. Note that this point is close to, but not always is, the median of the Pareto optimum solution set as the location of this point depends on the rate of change of the curve itself. For simplicity, this method is also adopted in this chapter and referred to as the equal-weighted (EW) solution. Having a single point also allows comparisons between various scenarios.

Ultimately, it is up to the homeowners to decide the shave factor proportion between GSHP and conventional systems. After all, they are the ones paying the installation and operational costs, and hence they should be the most important decision-maker. The results presented here may allow designers and engineers to let homeowners to be informed and make a decision. Homeowners can install at point A if they want to minimise costs. Alternatively, point C may be preferred if they want to minimise emissions and contribute more to the society. Otherwise, they can install at point D for example, if they want to both contribute to society with minimal extra financial costs. Other points are also an option depending on their criteria.

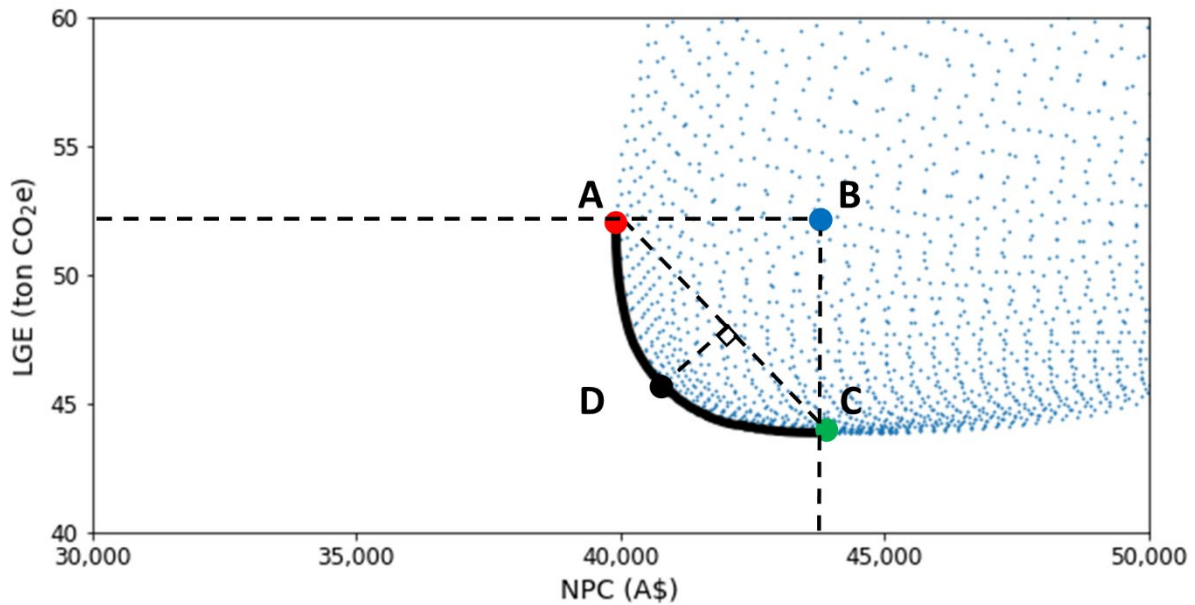


Figure 6-1: Example of a Pareto optimum solution. Points A and C are Pareto optimal, while point B is not

6.4 Results and discussions

In this section, results corresponding to Sydney, Hobart and Cairns are chosen to represent a balanced climate, a heating-dominant climate, and a cooling-dominant climate, respectively.

6.4.1 Pareto optimum solution for HGSHP systems under base case conditions

Figure 6-2 presents the NPCs and LGEs for each shave factor combinations for HGSHP1 and HGSHP2 in Sydney. The Pareto optimum solutions are represented by the black lines. Furthermore, the lowest NPC solution, the lowest LGE solution and the EW solution are provided. For HGSHP1, the lowest NPC for the 20-year lifespan of the system is approximately A\$40,000 with an LGE of 52 ton CO₂e. In contrast, if the HGSHP1 system is designed to minimise the LGE, the optimum design has an NPC of approximately A\$44,000 but with an LGE of 44 ton CO₂e. This 8 ton CO₂e savings seems low, but this value represents 15% of the total emissions (8/52). It is important to recognise that a 15% lifetime emission reduction is equivalent to over three year's worth of emissions caused by the heating and cooling usage in this house. The EW solution for HGSHP1 in Sydney has an NPC of A\$41,000 and an LGE of 44 ton CO₂e.

The Pareto optimum solutions for HGSHP2 systems in Sydney offer an interesting case where the lowest NPC, the lowest LGE and the EW solution have similar NPCs and LGEs of \$44,000 and 44 ton CO₂e. Overall, the difference between the lowest NPC and the lowest LGE solution is a lifetime cost and emission of \$500 and 0.5 ton CO₂e respectively. This will be discussed further below.

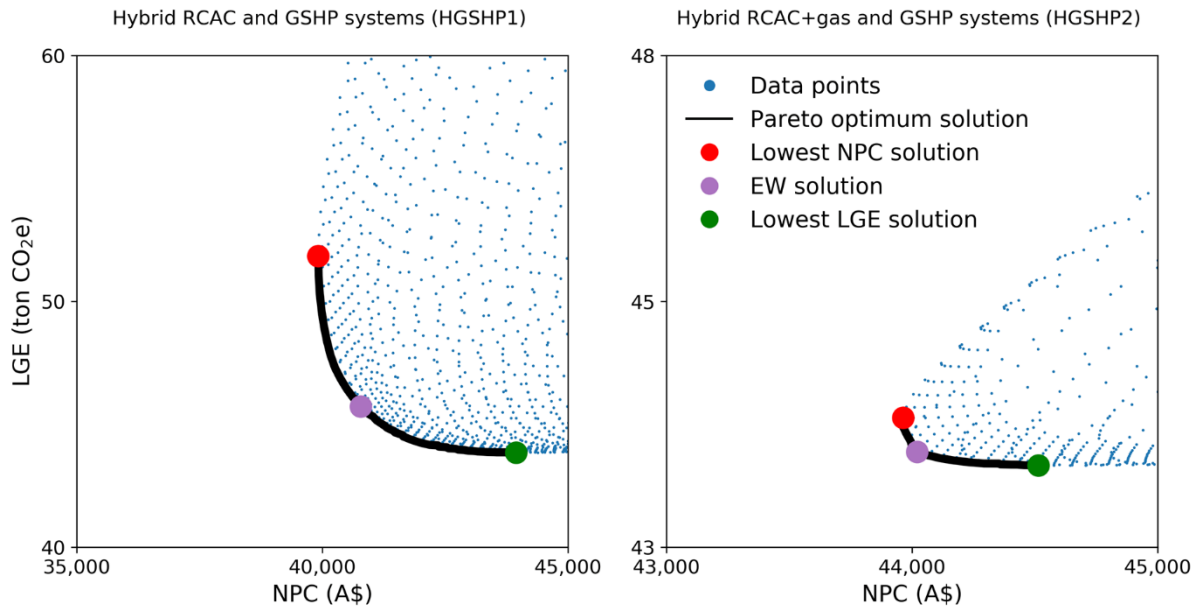


Figure 6-2: Pareto optimum solutions for HGSH1 and HGSH2 in Sydney

The results presented in Figure 6-2 offers an insight into the potential usage of HGSH1 and HGSH2 under Sydney’s climatic conditions to minimise the NPCs and the LGEs. However, further examination is needed to determine how much of the total peak load proportion needs to be provided by GSHP and conventional systems, which is commonly referred to as a *shave factor*. The shave factors need to be decided prior to the construction stage to achieve the desired level of NPCs and LGEs. To do this, the corresponding heating and cooling shave factor is presented in Figure 6-3 to complement the Pareto optimum solution set results presented earlier. The bottom left corners of the plots in Figure 6-3 represent a 0% shave factor or effectively conventional systems. The top right corners of the plots represent a 100% shave factor or effectively GSHP systems. The points in between represent different shave factor combinations for each HGSH system in Sydney. In this plot, the Pareto optimum solution is presented based on the relevant heating and cooling shave factors. The lowest NPC solution, the lowest LGE solution, and the EW solution are also provided.

GSHP system designers need the heating and cooling shave factor information presented in Figure 6-3 as they cannot design a GSHP system by aiming for the lifetime cost and emission values shown earlier. In this case, if homeowners request an HGSH1 system with the lowest lifetime costs, then designers are recommended to size the system for 32% heating and cooling shave factors. Similarly, to minimise the lifetime emissions, it is best to utilise a hybrid system with the GSHP component is designed to meet 90% of the peak heating and cooling load. The EW solution occurs at 52% heating and cooling shave factors.

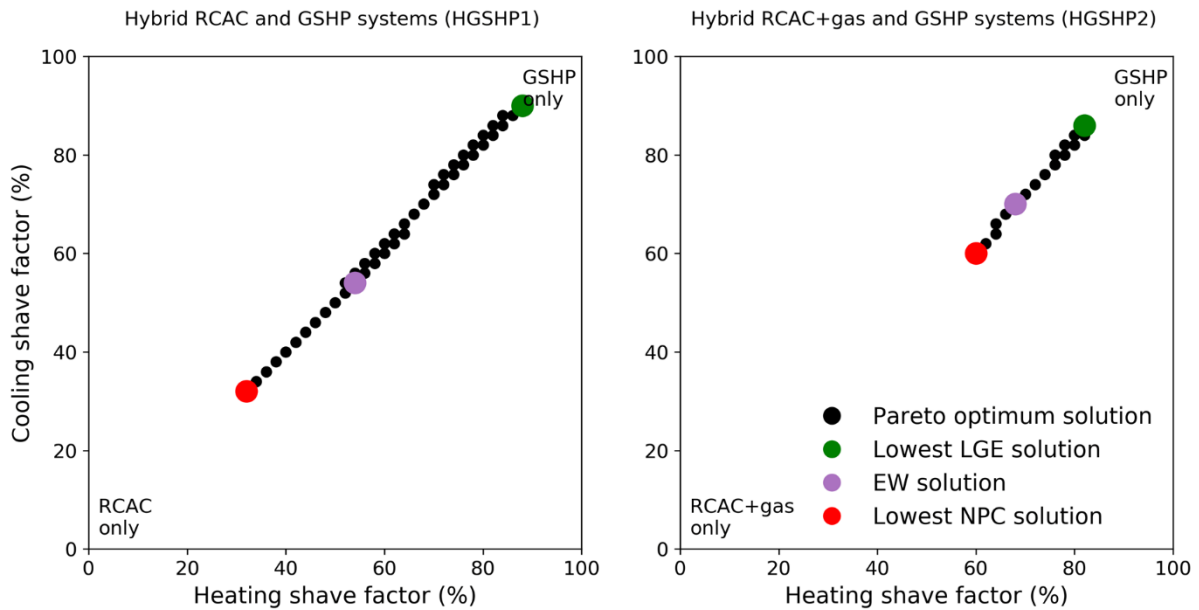


Figure 6-3: Heating and cooling shave factors corresponding to the Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney

The Pareto optimum solution for HGSH1 system shown in Figure 6-3 is almost exactly at the 45-degree line (i.e., equal heating and cooling shave factors). This suggests that both heating and cooling shave factors have some effect on the Pareto optimum solutions since buildings require both heating and cooling in Sydney. The Pareto optimum solutions sets also indicate a tradeoff between costs and efficiency. One of the major barriers for GSHP system adoption is the capital costs to install the GHE. Utilising a hybrid system enables users to take advantage of both the lower capital cost of a conventional system and the lower operational cost of a GSHP system. In this case, the system with the lowest NPC utilises a GSHP system, which is sized to meet 32% of the peak load needed in Sydney. A smaller GSHP system capacity means less GHE length required. This system is further supported by a conventional system, which is cheaper to install, but less efficient. The GSHP system able to satisfy around 75% of the annual thermal demand with this setup.

In contrast, the lowest LGE solution is for an HGSH1 system where the GSHP system is designed to provide around 90% of the peak heating and cooling load. It is important to note that at this point, this system is effectively a full GSHP system as 99% of the annual thermal demand can be satisfied. This makes sense since the average hourly CoP of the GSHP system is higher than the RCAC system. A more efficient system requires less electricity, thus resulting in lower lifetime emissions.

Another interesting observation is that the lowest LGE solution is not the GSHP system itself but an HGSH1 system at a 90% heating and cooling shave factors as outlined above. At this point, the GSHP is sized for 5.3 and 6.3 kW heating and cooling load respectively. Additional RCAC system is needed when the building requires the peak thermal demand of 5.8 and 7.3 kW of heating and cooling respectively. Based on the weather data, there are only 23 hours of the year (0.3%) when this happens. This means that the additional electricity savings and emissions for utilising a more efficient GSHP system during these hours are minimal. In contrast, a full GSHP system would require a bigger GSHP unit and a longer GHE length, which means higher initial costs and emissions. Overall, this results in a scenario where the lowest LGE solution has both lower NPC and LGE compared to a full GSHP system.

The Pareto optimum solution set presented for HGSHP2 systems in Figure 6-3 is relatively narrow compared to the solution set for HGSHP1 system. This suggests that the hybrid component mix between the lowest NPC and LGE solutions are quite similar. The lowest NPC solution is at 60% heating and cooling shave factors where the GSHP system is able to provide 96% of the annual thermal demand. The lowest LGE solution is at 82% and 86% heating and cooling shave factors where the GSHP system is able to meet 99% of the annual thermal demand. Since the GSHP system provides most of the annual thermal demand for both scenarios, hence it is not surprising that the lifetime costs and emissions for these scenarios are relatively similar.

HGSHP2 system offers the possibility to provide heating either by using electricity through a GSHP system or by using gas through a gas furnace. The cheaper option depends on the relative efficiency of both systems and the relative price of electricity and gas. In Sydney, the relative efficiency between GSHP and gas furnace is 5.2 (CoP of GSHP system is 4.7 divided by efficiency of 0.9 for a gas furnace). However, electricity is only 1.9 times more expensive than gas. This means that in HGSHP2 system, heating with a GSHP system is financially preferred compared to heating with a gas furnace as the alternative. This explains that the lowest NPC solution for HGSHP2 system has a higher heating and cooling shave factor (60%) than in HGSHP1 system (32%).

This observation suggests that when gas is available as a substitute fuel source for a heating system, then the analysis needs to be considered on a case-by-case basis. This substitution effect on the NPCs and LGEs can be complex, where they can depend on the climates, fuel costs, fuel emission factors and the efficiency of the relevant heating and cooling systems in each location.

The analysis is then repeated for a heating-dominant climate in Hobart. The Pareto optimum curve in Hobart for HGSHP1 and HGSHP2 is presented in Figure 6-4. For HGSHP1, the lowest NPC for the 20-year lifespan of the system is approximately A\$61,000 with an LGE of 20 ton CO_{2e}. Figure 6-5 indicates that this lowest NPC point occurs when the HGSHP1 system is sized for 24% and 36% heating and cooling shave factors, respectively. It should be noted that this cooling shave factor is practically irrelevant as there is a minimal need for cooling in Hobart (0.6 MWh annually). In this scenario, the GSHP system only able to meet 60% of the annual thermal demand. Despite that, the GSHP is sized to meet a small proportion of the peak heating load (2 kW from a peak of 8.4 kW). Since Hobart is highly heating dominant, then providing the full heating load with the GSHP system would result in a significantly longer GHE length and much higher installation costs. Therefore, a greater proportion of RCAC system is preferred if the goal is to minimise costs.

In contrast, if HGSHP1 is designed to minimise the LGE, then it has an NPC of A\$66,000 and an LGE of 17 ton CO_{2e}. This solution requires the GSHP system to meet 78% of the peak heating load, but able to meet 99% of the annual energy demand. The EW solution has an NPC of A\$62,000 and an LGE of 18 ton CO_{2e}, where the GSHP needs to be sized to meet 46% of the peak heating load (4 kW).

A similar, but shorter, range of Pareto optimum solutions can be observed for HGSHP2 systems in Hobart. The lowest NPC, the lowest LGE and the EW solution in Figure 6-4 have NPCs between A\$62,000 and A\$65,000 while LGE between 17 and 18 ton CO_{2e}. The price and emission ratio of electricity and gas is even smaller in Hobart (1.6) compared to the same ratio in Sydney (1.9). However, the efficiency ratio between GSHP system and gas furnace in Hobart is smaller than in Sydney since GSHP system in Hobart operates less efficiently throughout the whole year due to the high heating dominant climates in Hobart. Despite this GSHP is still a much more efficient system compared to a gas furnace, which results in a very narrow Pareto optimum solution range as shown in Figure 6-5. The lowest NPC, EW and lowest LGE solution requires 64%, 72% and 84% heating shave factor respectively.

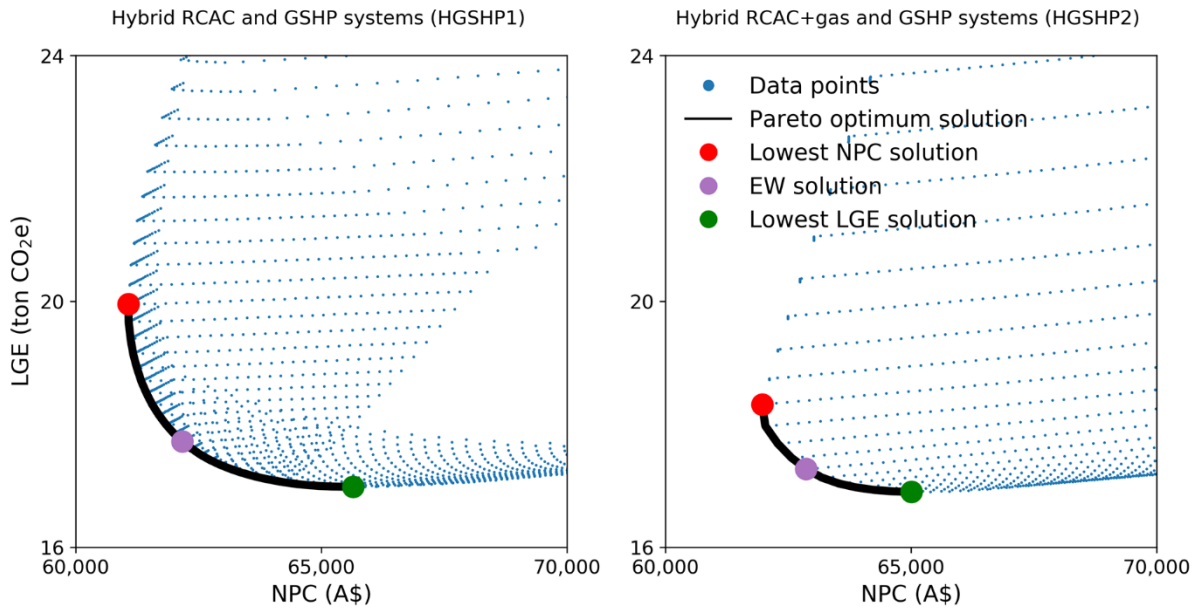


Figure 6-4: Pareto optimum solutions for HGSH1 and HGSH2 in Hobart

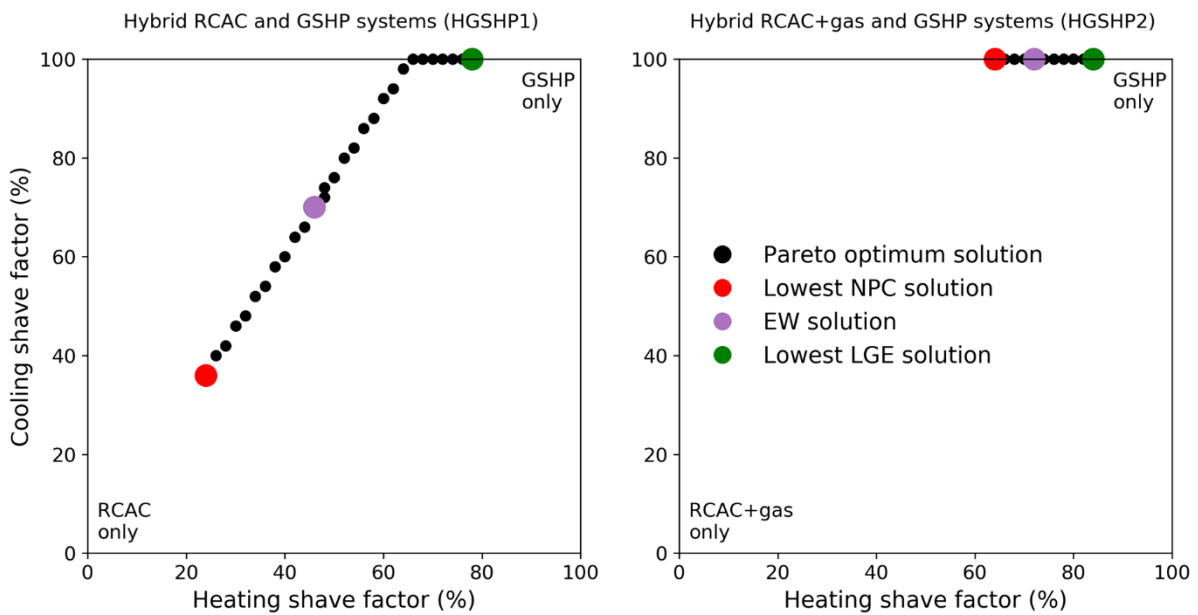


Figure 6-5: Heating and cooling shave factors corresponding to the Pareto optimum solutions for HGSH1 and HGSH2 systems in Hobart

The Pareto optimum solution for HGSH1 in Cairns is presented in Figure 6-6, along with the corresponding heating and cooling shave factor combinations. Only the result for HGSH1 is presented here as Cairns requires a very low heating requirement of 0.4 MWh. Hence, a gas furnace or an HGSH2 system is not needed. For HGSH1, the lowest NPC for the 20-year lifespan of the system is approximately A\$66,000 with total GHG emissions of 100 ton CO₂e. This optimised point is at 38% cooling shave factor. Although heating shave factors are used in this analysis, they are practically irrelevant due to the minimal heating need in Cairns.

If HGSH1 is designed to minimise the LGE, then it has an NPC of A\$70,000 with a much lower LGE of 87 ton CO₂e, and at this point, it is practically a GSHP system since the GSHP is sized to meet 92% of the peak cooling load and able to meet 99% of the annual thermal demand.

The EW solution has an NPC of A\$67,000 and an LGE of 90 ton CO₂e. For this solution, the GSHP needs to be sized to meet 60% of the peak cooling load. This EW solution offers an interesting decision-making scenario for homeowners. In comparison to the lowest NPC solution, this EW solution can reduce the lifetime emissions by 10 ton CO₂e (10%), but only an additional A\$1,000 (2%) is needed to make this happen.

This section has demonstrated the potential to optimise HGSH1 systems considering the trade-off between their lifetime costs and emissions. The single most optimum point from this solution set, however, will need to be decided by the relevant stakeholders given the relevant weighted importance of both variables.

An HGSH1 system typically has different shave factor combinations to represent a design which has the lowest lifetime costs and emissions. HGSH2 offers a slightly more interesting case where there is a trade-off between the usage of gas and electricity. In this scenario, the relative price ratio between electricity and gas, the electricity-to-gas-emission factor ratio, and the efficiency of the heating and cooling systems can play some effect. This suggests the importance of investigating this on a case-by-case basis. For this reason, the next section will investigate the potential impact if there are some changes to the key parameters considered in this base case.

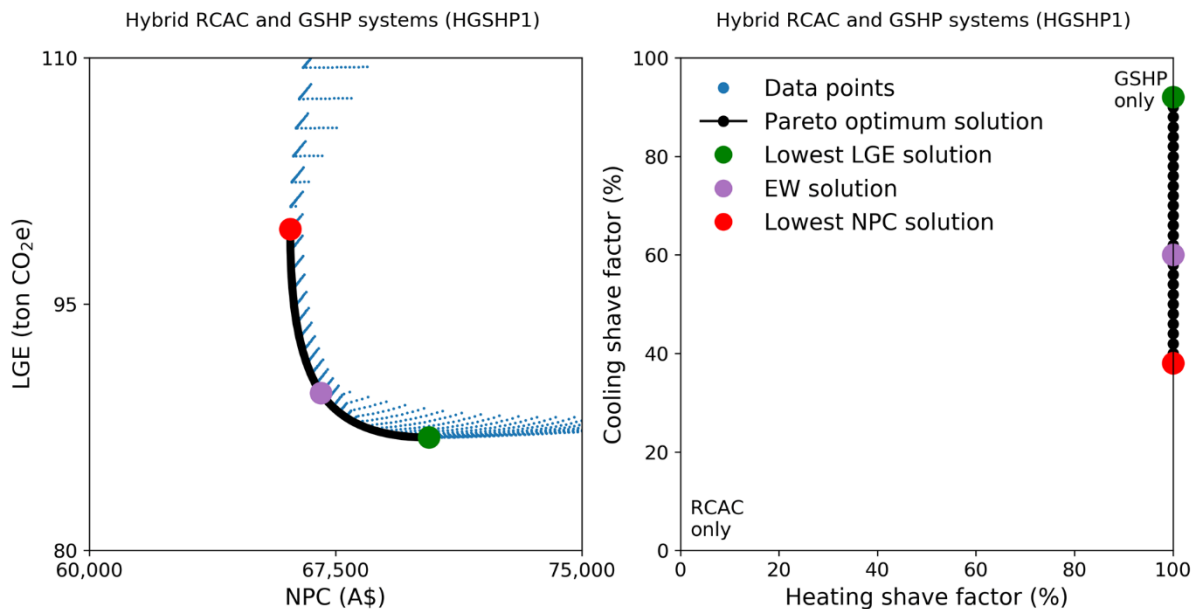


Figure 6-6: Pareto optimum solutions and their corresponding heating and cooling shave factors for HGSH1 systems in Cairns

6.4.2 Impact of changes in drilling cost for GHEs

The analyses presented in the previous sections were conducted with a GHE drilling cost of A\$80/m, as typically found in Australia [41]. In this section, the GHE drilling costs are adjusted to A\$50/m, A\$100/m and A\$150/m. The lowest cost reflects costs in a more competitive and mature GSHP system industry, while the two highest costs reflect less favourable conditions where, for example, more difficult ground conditions are encountered. The values of all other parameters have been maintained.

Figure 6-7 presents the Pareto optimum solutions for HGSH1 and HGSH2 in Sydney, Hobart and Cairns with various GHE drilling costs. An increase in drilling costs results in the Pareto optimum

curve shifting to the right. Furthermore, the range of the Pareto optimum curve also widens, especially for HGSHP1 systems.

The Pareto optimum solution is mostly governed by the costs required and emissions generated during the operational stage of the systems as the costs and emissions add up over 20 years life-span of the systems. Since the relative efficiency of a GSHP system to an RCAC system is smaller than a GSHP system to a gas furnace, then an increase in capital costs (as drilling cost increases) should have more effect in an HGSHP1 system compared to an HGSHP2 system. This is represented by the significant change in the possible range of Pareto optimum solutions in HGSHP1, whereas only small changes occur in HGSHP2, as shown in Figure 6-7. This change reflects that, as drilling cost increases, the RCAC system becomes more competitive, and hence a higher usage proportion is desired in the hybrid system mix. In fact, for HGSHP1 system, the lowest NPC solution in all three cities when the drilling cost is A\$150/m is effectively the conventional RCAC system. But, this is not the case for HGSHP2 system at this A\$150/m drilling cost scenario. A more significant increase in drilling cost is required for the HGSHP2 system to have a more noticeable effect on the Pareto optimum curve for HGSHP2.

In Figure 6-7, as drilling cost is increased, the lowest NPC solutions experience an increase in both their NPCs and LGEs. It should be noted that each of these lowest NPC solutions refers to different heating and cooling shave factor combinations. As GHE drilling cost increases, GSHP systems become more expensive, and thus a greater proportion of conventional systems is preferred. Since a conventional system is less efficient than a GSHP system, then more electricity is required to run the system, thus resulting in higher lifetime costs and emissions.

In contrast, when the drilling cost is increased, only the NPC changes for the lowest LGE solution, while the LGE values remain unchanged. This indicates higher lifetime costs (reflecting higher installation costs) while the total emissions stay the same. This makes sense as an increase in drilling costs should not change the lifetime emissions as the emissions depend on energy consumption. As before, all these lowest LGE solutions are effectively the GSHP systems at each location.

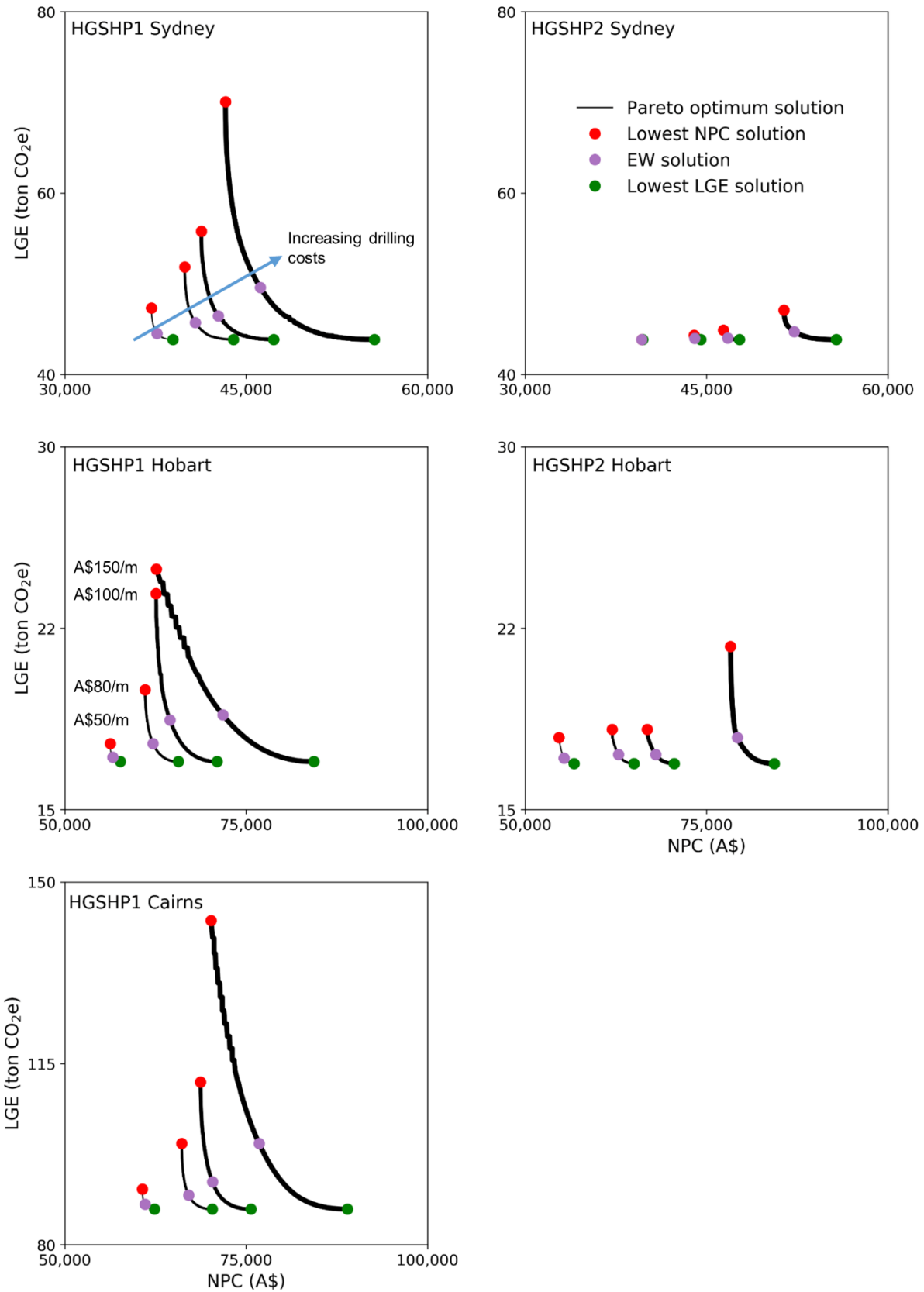


Figure 6-7: Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney, Hobart and Cairns with a drilling cost of A\$50/m, A\$80/m A\$100/m and A\$150/m

6.4.3 Impact of changes in thermal conductivity of the ground

In this section, various ground thermal conductivity values (λ) are investigated, with the λ values varying from 0.7 to 2.5 W/m.K. These values have been chosen to represent typical soils such as clay, silt and sand; both in saturated and unsaturated conditions as measured by Bose [163]. Other parameters are kept the same in this section.

A decrease in λ causes an increase in GHE length and in turn is expected to increase capital costs to install GSHP and HGSHP systems. Figure 6-8 presents the Pareto optimum solutions for HGSHP1 and HGSHP2 in Sydney, Hobart and Cairns when the λ is decreased. Overall, decreasing λ causes the Pareto optimum solutions curve to shift to the right, indicating higher lifetime costs and emissions generated by the systems. The increase in costs is not too significant since a decrease in λ only affects the capital cost component of the system and this costs increase will then distributed throughout the lifetime of the systems.

The lowest LGE solutions shift to the right as decreases, which indicates an increase in NPCs and LGEs. The increase in the LGEs is minimal, except for the case in Hobart. A longer GHE length means more emissions generated during the drilling process. For the cases in Sydney and Cairns, the emissions generated through the operation of the systems are much more significant due to the high electricity emission factor at those locations. This means that the increase in drilling-related emissions is relatively minor in Sydney and Cairns. In contrast, the electricity emission factor in Hobart is significantly lower, which means that any changes in drilling-related emissions would contribute to the lifetime emissions more significantly.

Furthermore, the corresponding heating and cooling shave factors for the lowest LGE solutions also decreases as λ increases. As drilling-related emission increases, it is logical that the hybrid system with the lowest lifetime emissions would need a shorter GHE length, which causes a higher proportion of conventional system is required. For example, for HGSHP1 system in Hobart, the lowest LGE solution when λ is 2.5 W/m.K has a corresponding heating shave factor of 78%. At this point the GSHP system component can provide 99% of the annual thermal demand. If λ is 0.7 W/m.K, then the HGSHP1 component has a GSHP with a heating shave factor of 68% and able to provide 98% of the annual thermal demand.

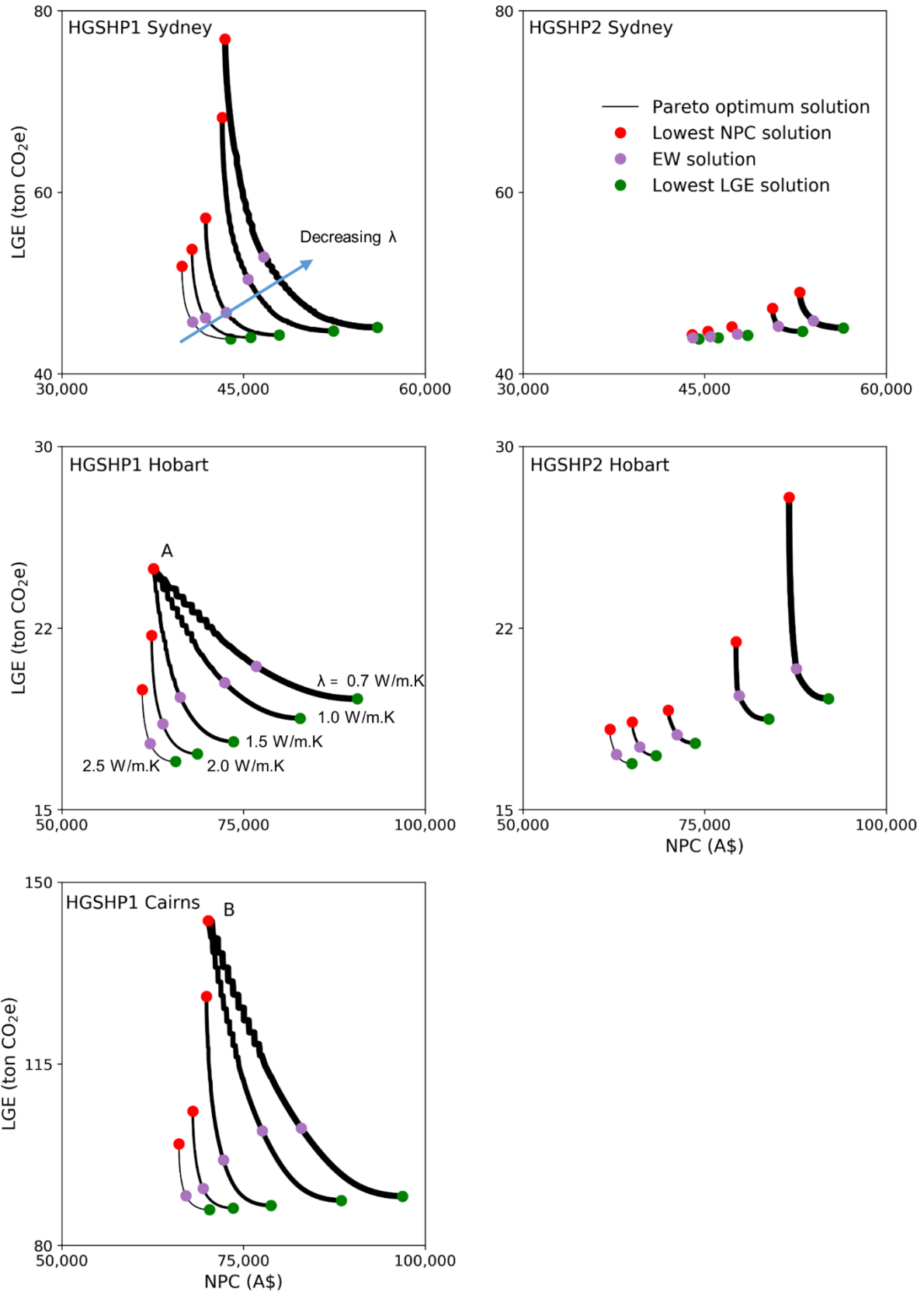


Figure 6-8: Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney, Hobart and Cairns when the ground thermal conductivity (λ) decreases

For the lowest NPC solutions, decreasing λ causes both the NPCs and the LGEs to increase, where the increase in the LGEs is much more significant as λ decreases, especially for the HGSHP1 system. The increase in GHE length needed means that a higher proportion of conventional systems is preferred to be more cost-efficient in the hybrid configuration. Therefore, as λ decreases, the lowest NPC solution corresponds to lower heating and cooling shave factors. In fact, this lowest NPC solution is the conventional system (RCAC) for HGSHP1 in Hobart and Cairns when λ has decreased to 1.5 W/m.K and 1 W/m.K, respectively. This is represented by points A and B in Figure 6-8. This means that at such a point, the GHE installation costs have become too expensive due to the significantly long GHE requirements caused by poor ground thermal conductivity. Hence, it is preferred to install conventional systems without any GHEs. For this reason, a further decrease in λ has no effect as GHE is not required and an RCAC system is used at this point. The effect described above is less apparent for the HGSHP2 system since a GSHP system is significantly more efficient than a gas furnace system. Hence, only a drastic decrease in λ (such as to 0.7 W/m.K) affects the range of possible Pareto optimum solutions such as for the HGSHP2 system in Hobart.

6.4.4 Impact of changes in energy prices

The last two sections have presented the effect of potential changes in capital costs of the system. In this section, potential changes in operational cost are investigated by varying energy prices. Energy prices may change depending on the market forces in the future energy sector. It is difficult to gauge future energy prices in Australia due to the large dependency on fossil fuel here. The future energy prices may increase due to fossil fuel scarcity but may decrease if a greater portion of renewable energy is used instead. For this reason, the electricity and gas prices presented in Table 6-5 are decreased by 50% and increased by 50% and 100% to potentially reflect these changes. The effect of these energy price changes is investigated when the energy prices are changed individually or together. Changing these prices individually also changes the energy price ratio between electricity and gas, whereas changing these prices together will keep this ratio unchanged.

Figure 6-9 presents the case for HGSHP1 system when the energy price is changed. Since HGSHP1 system only uses electricity, then changing the energy price together or individually should result in the same effect as the price of gas is irrelevant for HGSHP1 system. It can be observed in Figure 6-9 that the Pareto optimum solution curve shifts to the right, indicating higher lifetime costs. Furthermore, the curve also gets narrower as the energy price is increased in each city. In the HGSHP1 system, increasing the price of electricity represents a direct trade-off between GSHP and RCAC systems since both require electricity to run. A more efficient GSHP system is preferred when the energy price is increased. In contrast, the RCAC system is preferred when the energy price is low.

For the same reason, the lowest NPC solution corresponds to a different hybrid system mix for each price scenario at each city. When the energy price is low, the lowest NPC solution is the RCAC system at each location. This also explains that this lowest NPC solution has high emissions as RCAC system requires more electricity consumption. As energy prices increases, the lowest NPC value refers to a higher proportion of GSHP system usage. For example, when the energy prices are doubled in Sydney, the lowest NPC in HGSHP1 system configuration has the GSHP unit sized to meet 52% of the peak heating and cooling load but able to meet 93% of the annual thermal demand. This 52% shave factor is significantly higher compared to the 32% shave factor in the base case.

The lowest LGE solution for each scenario is effectively the GSHP system as described in previous sections. The corresponding heating and cooling shave factors for this lowest LGE solution remains unchanged even when the energy price is changed.

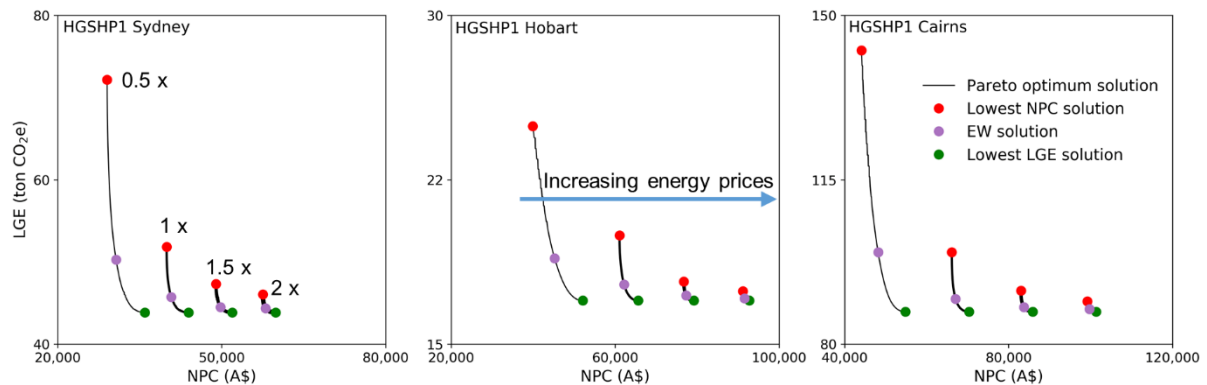


Figure 6-9: Pareto optimum solutions for HGSH1 systems in Sydney, Hobart and Cairns when both energy prices are multiplied by 0.5, 1, 1.5 and 2

The effect of changing energy price is more complex in the HGSH2 system due to the possible substitution effect between electricity and gas. Furthermore, the effect may be different when the energy prices are changed individually or together. Hobart is chosen to show the results since it is heating-dominant and expected to be more price-sensitive to this substitution effect when the gas price is changed.

The effect of changing energy prices for HGSH2 system in Hobart is presented in Figure 6-10. The impact of changing both prices simultaneously is similar to that of HGSH1 systems, where the Pareto optimum solution shifts to the right, indicating higher lifetime costs. However, changing the energy price simultaneously has a much smaller impact in the Pareto optimum solution range in HGSH2 system compared to in HGSH1 system. The lowest LGE solution is effectively the GSHP system, sized to provide 84% of the peak load but able to meet 99% of the annual thermal demand. The heating shave factor corresponding to the lowest NPC solution changes from 60% to 66% when both of the energy prices are changed from half of the current price to double the current price.

A gas furnace becomes more attractive when only the price of electricity is increased while keeping the gas price the same. This results in a slight increase in the range of Pareto optimum solutions as shown in Figure 6-10. The lowest LGE solution is the same as before, which is with a GSHP system sized to meet 84% of the peak load. The lowest NPC solution requires different heating shave factor depending on the price of electricity considered. When the price of electricity is doubled, the HGSH2 system needs to have its GSHP unit sized to meet 58% of the peak heating load, but still able to meet 95% of the annual thermal demand.

Similarly, a gas furnace becomes more financially attractive when the gas price is decreased. The gas price becomes so low that heating by a gas furnace is much desired. At this point, the lowest TNC solution occurs when the GSHP system is sized at 10% of the peak heating load. With this configuration, the GSHP system provides 30% of the annual thermal demand while the gas furnace provides 70%. However, this high gas consumption yields a significantly higher LGE (66 ton CO₂e). The lowest LGE solution remains the same where the GSHP unit sized to meet 84% of the peak heating load. This is indicated as point A in Figure 6-10. Since this point is effectively a GSHP system and only uses electricity, then point A represents all of this lowest LGE solution at any gas price.

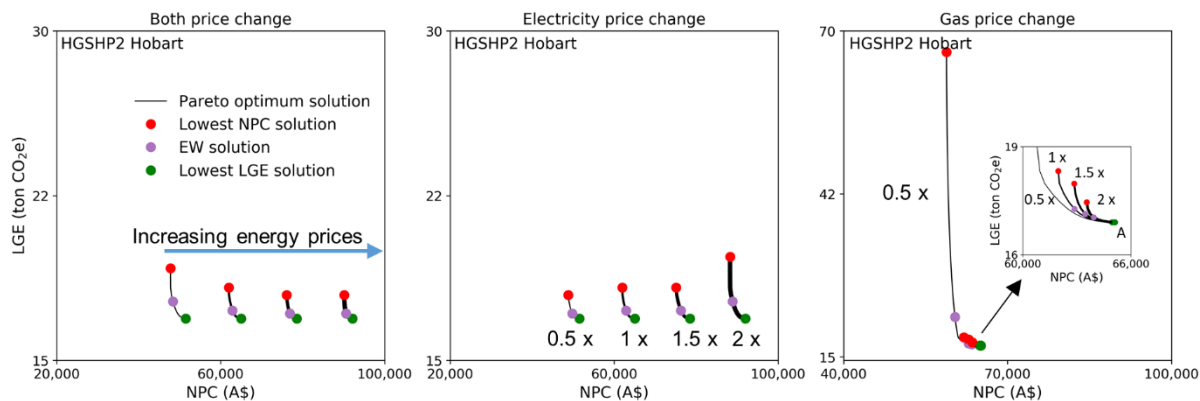


Figure 6-10: Pareto optimum solutions for HGSH2 systems in Hobart when energy prices change together and individually

6.4.5 Impact of changes in CoPs of RCAC and GSHP systems

The CoP of the RCAC and GSHP system influence how much electricity is consumed, which in turn determine the annual operating costs and emissions. The CoP values used in the above analysis was based on a specific heat pump unit with its relevant performance curve specified by the manufacturer. In this section, this CoP performance curve is adjusted by ± 0.5 to reflect a possible higher or lower efficient heat pump. Hence, on average, the CoP for an RCAC system in Sydney is around 2.6 ± 0.5 and the CoP for a GSHP system is 4.7 ± 0.5 . For simplicity, the efficiency of a gas furnace is kept the same (0.9) as this value represents the combustion rate of gas.

Figure 6-11 presents the effect when the RCAC's CoP is adjusted. The changes in RCAC's CoP mostly affect the HGSH1 system as it is purely a mix of GSHP and RCAC systems. As the CoP of RCAC decreases, the Pareto optimum solution range gets narrower in all three cities. The lowest LGE solutions slightly shift to the right indicating a slightly higher shave factor mix, but they are all effectively a hybrid system with the GSHP component providing 99% of the annual thermal demand.

The lowest NPC solution has a higher NPC but a lower LGE when the RCAC's CoP is decreased. The GSHP system becomes more attractive as a less efficient RCAC unit is used. This results in a higher shave factor mix. Furthermore, utilising a more efficient GSHP system would reduce the lifetime emissions. In contrast, if a more efficient RCAC unit is used instead, the RCAC unit becomes the most cost-effective option. This is the case in Hobart and Cairns when the chosen RCAC unit has its CoP increased by 0.5.

The impact of changing the efficiency of the chosen GSHP unit is shown in Figure 6-12. Using a less efficient GSHP unit shifts the Pareto optimum solution to the top right corner for both HGSH1 and HGSH2 system. Lower efficiency means more electricity consumption, which further increases NPCs and LGEs. Furthermore, lowering GSHP's CoP also makes a conventional system to be more attractive and this is indicated by the slight increase in the range of the Pareto optimum curve.

Similar to the above, HGSH1 system is more sensitive to this efficiency changes as it represents a direct financial trade-off between GSHP and RCAC system. In this case, the lowest NPC solution gets closer to the conventional system as GSHP's efficiency decreases. In fact, the RCAC system is the lowest NPC solution in Hobart if a lower efficiency GSHP unit is used here.

Changing the efficiency of GSHP system has minimum impact on the hybrid shave factor mix for HGSHP2 systems in Sydney and Hobart. The reason behind this is a GSHP system is far more efficient compared to a gas furnace and the electricity to gas price ratio is relatively low in Australia. GSHP system is still preferred even when the CoP of the GSHP system is reduced by 0.5. However, if the GSHP CoP were reduced further and/or if the electricity and gas price ratio were to increase, then a conventional system may be preferred.

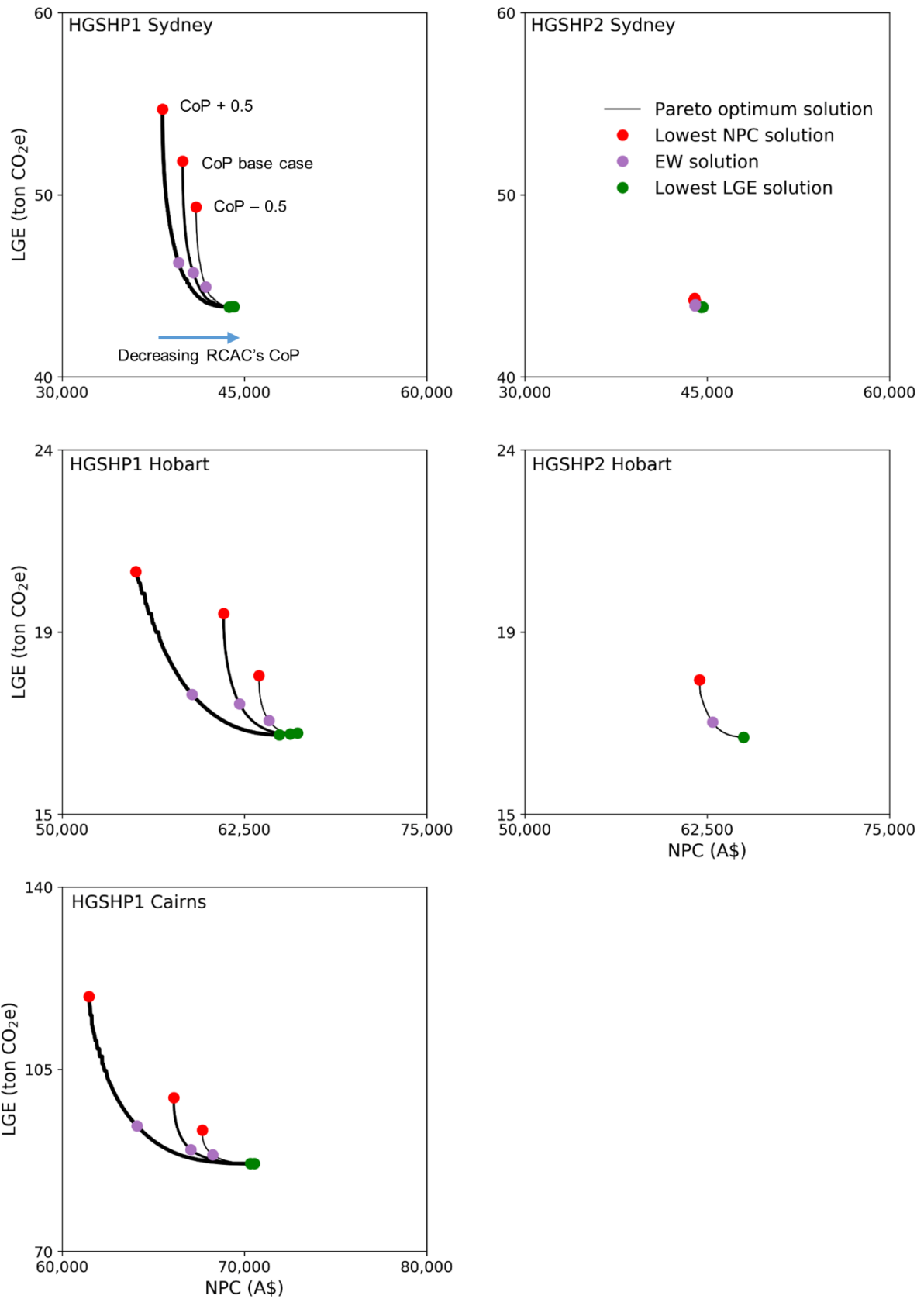


Figure 6-11: Pareto optimum solutions for HGSHP1 and HGSHP2 systems in Sydney, Hobart and Cairns for RCAC's CoP of different CoPs

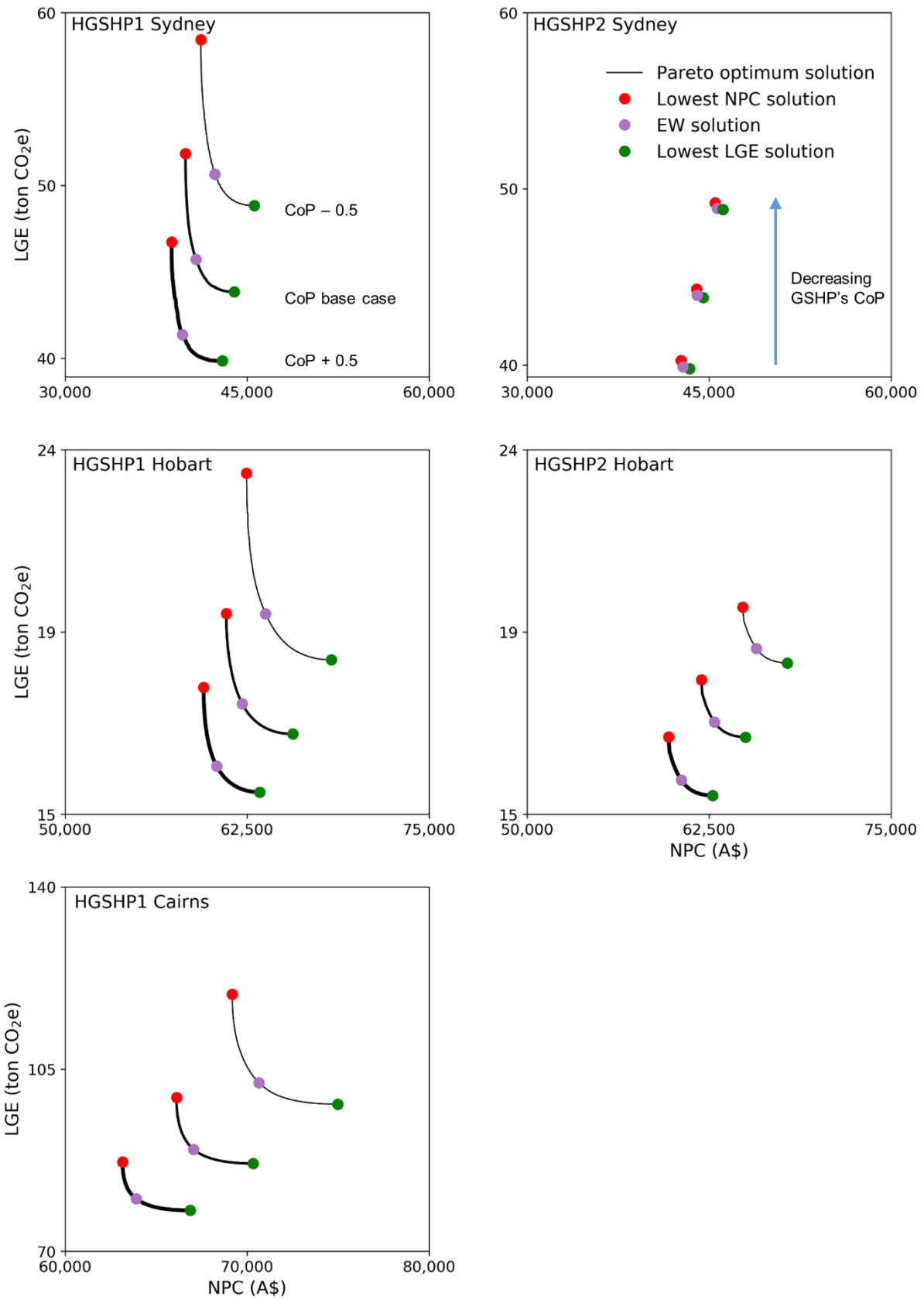


Figure 6-12: Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney, Hobart and Cairns for GSH's of different CoPs

6.4.6 Impact of changes in emission factors

Sydney and Cairns have relatively high electricity emission factors due to the high proportion of fossil fuel used in the electricity generation fuel mix. This electricity emission factor is expected to decrease over time as more renewable energy is used as part of the fuel mix. In this section, the potential for 25%, 50% and 75% reduction in this electricity emission factor is considered for the cases in Sydney and Cairns. The electricity in Hobart is assumed to be unchanged since most of it is already generated from renewable hydro sources. Up to 75% potential decrease in emission factor is considered in Sydney and Hobart to make these values closer to the one in Hobart. Furthermore, the gas emission factor is assumed unchanged because this depends on the combustion rate of gas.

In Figure 6-13, the Pareto optimum curve shifts downward as the electricity emission factor decreases, which represents lower lifetime emissions for all scenarios. Despite these drastic changes in the emission factor, there is minimal effect in the Pareto optimum solution curve. The lowest NPC solutions in each case refer to the same heating and cooling shave factors. They have the same NPCs but the LGEs value decrease depending on the electricity emission factor.

The lowest LGE solutions follow a different pattern for HGSHP1 and HGSHP2 system when this emission factor is decreased. HGSHP1 system only requires electricity to run. A lower electricity emission factor resulting in a lower lifetime emission. This means that the initial emission from GSHP system installation (including drilling for GHEs) becomes a larger and more significant component of the lifetime emission. This encourages the hybrid system to adopt a lower proportion of the GSHP system component with a lower GHE length requirement. This is represented by the Pareto optimum curve gets slightly narrower in Figure 6-13, where more conventional system usage is preferred.

In contrast, when gas is available as a substitute, a lower electricity emission factor increases the attractiveness for providing heating and cooling by using a GSHP system. Initially, using electricity generates more than four times the emission than using gas, but the total annual GHG emission is still lower when using a GSHP system powered by electricity due to its higher efficiency. In the lower emission scenario, not only that GSHP system is more efficient, but electricity and gas emit similar amount of emissions. Hence, a GSHP system is much more preferred. This can be observed in Figure 6-13 where the Pareto optimum curve gets slightly longer for the HGSHP2 system in Sydney when the electricity emission factor reduces.

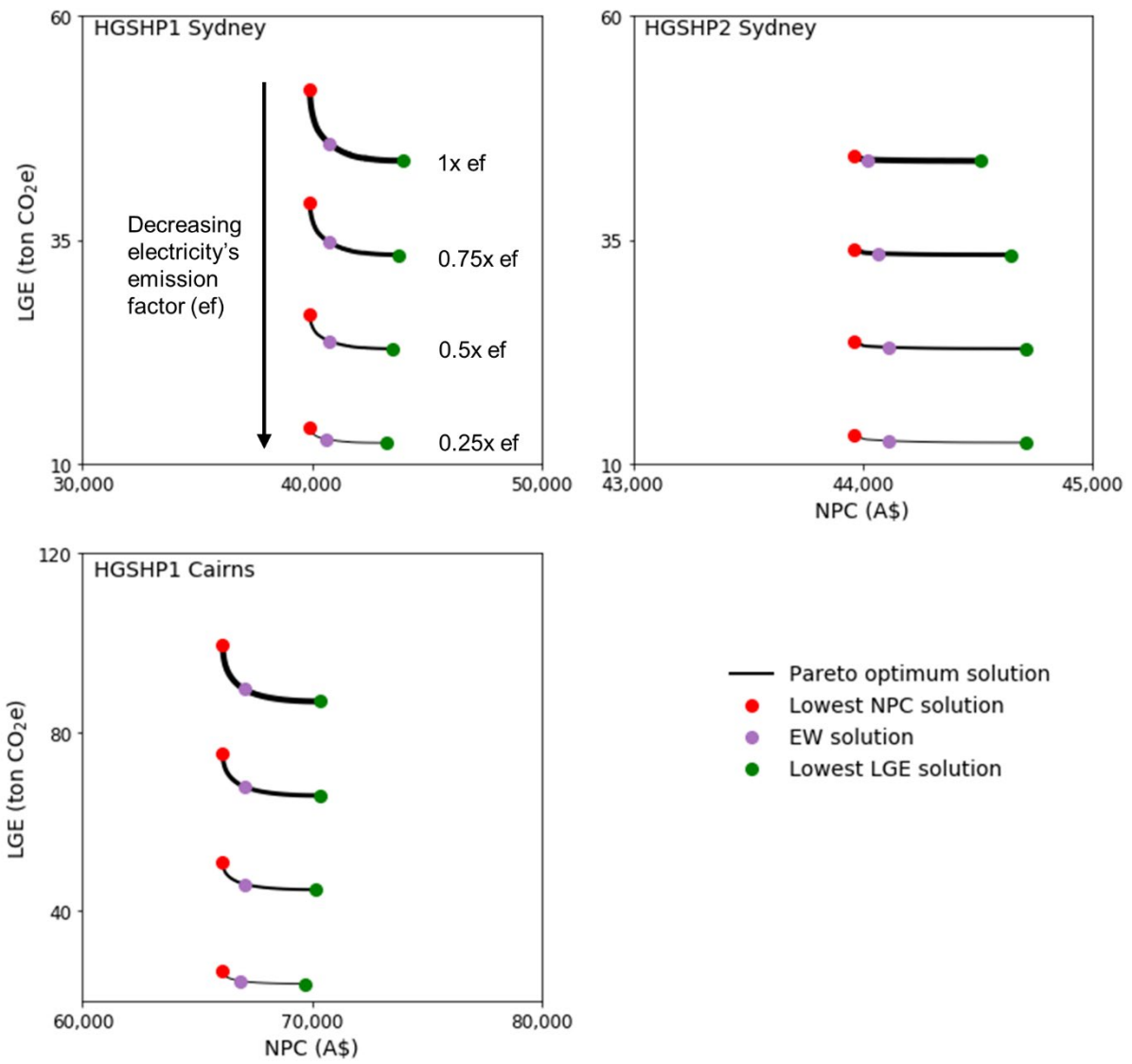


Figure 6-13: Pareto optimum solutions for HGSHP1 and HGSHP2 systems in Sydney and Cairns when the electricity emission factor decreases

6.5 Conclusions

In this chapter, a multi-objective optimisation method is adopted where the economic and environmental performance of hybrid ground source heat pump (HGSHP) systems in seven Australian cities are investigated. Two hybrid systems are considered. The first is a combination of a ground source heat pump (GSHP) system and a reverse cycle air conditioner (RCAC) system, and the second is a combination of a gas furnace, an RCAC for cooling and a GSHP system. A Pareto optimal approach is utilised to find the optimum solution set that considers both financial and environmental benefits of HGSHP systems.

The results suggest that the hybrid system combination with the lowest lifetime costs is often different than the one with the lowest lifetime emissions. It turns out that they are affected by the climatic conditions, efficiency of the systems, energy price ratio between electricity and gas and the emission factor ratio between electricity and gas.

The second part of this chapter considers the impact when any of these variables change. Changes such as an increase in energy price or an increase in the efficiency of the GSHP system or a decrease in the emission factor ratio typically result in the GSHP system being preferred. This is often indicated by the Pareto optimum solution range getting narrower and the lowest cost and emission solution converging as the GSHP system. On the contrary, changes such as an increase in drilling costs or an increase in the efficiency of the conventional system cause a higher proportion of conventional systems to be preferred. A conventional system can be preferred in some extreme cases. One example is when the cost to install the ground heat exchanger component for the GSHP systems becomes too expensive because the system is installed in a heating-dominant climate such as Hobart and in a location with very poor ground thermal conductivity. When a conventional system is preferred, the Pareto optimum solution range is relatively wide and the lowest cost and emission solutions can differ significantly.

The sensitivity analysis presented here suggests that the costs and emissions generated through operating the systems dominates the lifetime costs and emissions. This is shown where changes in factors that contribute to the operational of the system, such as the energy prices and the efficiency of both GSHP and RCAC systems have a more significant effect on both of the lifetime costs and emissions of the systems. In contrast, others factors that arise from the installation of the system, such as the drilling costs and thermal conductivity of where the system is installed at, only have minor effect on the lifetime costs and emissions of the systems.

Overall, the results presented here allow homeowners to make informed decisions for choosing their heating and cooling systems based on climatic, location, cost and emission conditions. Depending on the desired objective, one has the choice to minimise their lifetime costs or emissions. A solution which considers both the lifetime costs and emissions with equal weight was also provided.

7 District ground source heat pump systems for temperate climatic conditions

7.1 Overview and structure

This chapter investigates the possibility of connecting hybrid GSHP systems in several buildings into a district configuration (DHGSHP systems). This is possible because buildings are located close to each other in urban areas. The unique thermal load demand in each building may help the buildings to indirectly heat and cool each other. This will reduce the overall thermal demand of the buildings that needs to be supplied by the ground and improve the viability of hybrid GSHP systems. This chapter aims to provide a methodology to size the district system (DGSHP). The financial and environmental benefits of DGSHP systems are compared against individual systems for Australian (mostly temperate) climatic conditions.

A paper titled “District ground source heat pump systems for temperate climatic conditions” based on this chapter has been submitted to the journal *Applied Thermal Engineering*. However, to maintain consistency with thesis the full text of the paper is presented here. This chapter and publication are the author’s original work. Co-author authorisation forms have been included in this submission.

7.2 Introduction

The use of traditional district heating system is relatively common, customers purchased a total of 11.5 EJ of heat from worldwide energy providers in 2014 [180]. This heat is sourced from various energy sources, such as from waste heat, electric and gas-fired boilers and high and low temperature geothermal sources. In contrast, the development of district cooling is much smaller than its counterpart, where it was reported in 2017 that the worldwide total district cooling demand was 200 PJ [180], approximately 58 times lower than district heating. For district cooling, the coolth water supply is provided by natural cold resources and chillers. The use of chillers can be substituted with reversible heat pumps.

Traditionally, the district heating system uses steam or pressurised hot water as their heat carrier. The high temperature of these various heat carriers typically results in a large thermal loss during transmission to buildings and also poses a safety danger in case of explosion [181]. The same authors have also noted the development trend in district heating and cooling technology by using a lower temperature heat carrier to minimise these risks. This also leads towards the so-called “fourth generation district heating”, where district heating and cooling provide thermal energy to energy efficient buildings that are integrated with smart energy systems. One way to achieve this is by using a low temperature and renewable thermal energy source, which is accessed by using a ground source heat pump (GSHP) in district arrangements.

GSHP systems have increasing popularity, the total worldwide installed capacity increased by 34% between 2010 and 2015 [6]. In urban environments, buildings are often located near each other, which allows the possibility for district use of GSHP systems. This is referred to as a “district ground source heat pump (DGSHP) system” and is the focus of this chapter. In DGSHP systems, multiple buildings are connected to systems of GSHPs, through a common water loop between each individual building, as shown in Figure 7-1 below. If needed, additional conventional systems can be installed to support the DGSHP systems during the hottest and coldest day of the year.

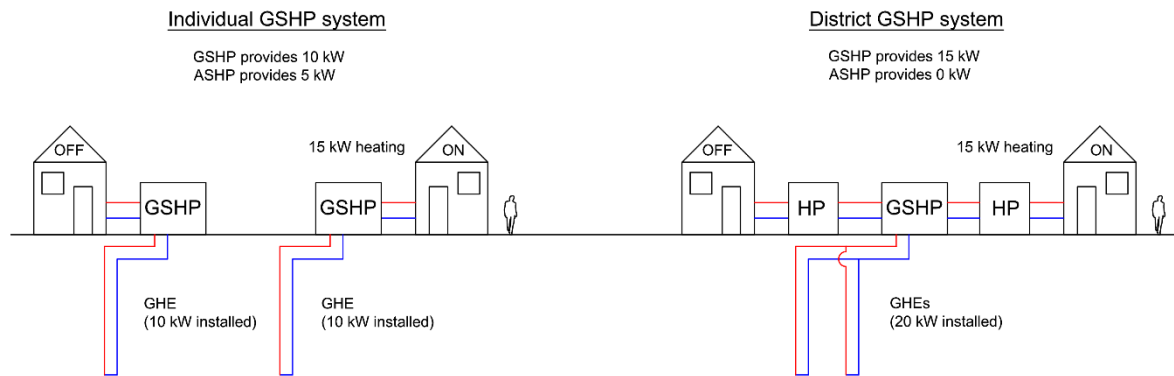


Figure 7-1: Schematic of individual (left) and district (right) ground source heat pump systems

In Figure 7-1, a comparison is made between individual GSHP and DGSHP systems. The DGSHP systems can share thermal loads between buildings depending on their energy occupancy patterns (*load sharing*). Each one of the individual buildings in Figure 7-1 (left) has a 10 kW GSHP system installed and the houses are supported by traditional reversible air source heat pump (ASHP) systems for the hottest or coldest day of the year if needed. Imagine a situation when one of the buildings has its occupants at home and requires a 15 kW heating demand to be satisfied, whereas the occupants of the other building are away. In the individual GSHP system configuration, the GSHP can only provide 10 kW of heating and an additional 5 kW is needed from the ASHP system. In contrast, in a district configuration, the DGSHP system is designed to provide 20 kW between both buildings and is able to satisfy all the thermal demand in this scenario by using the GSHP and without the need to use the less efficient ASHP. Although the total thermal load is the same between both the systems at this particular time (15 kW), the DGSHP system requires less electrical energy because all the thermal load is provided by the GSHP system, which is more efficient than the ASHP system. This should help to reduce the overall operational costs of the systems.

Another benefit of DGSHP systems is the ability to combine thermal energy demand between buildings (*load pooling*). Alavy et al. [100] described that buildings can indirectly help to heat and cool each other without the need to use the GSHP. If one building requires cooling, it can reject the heat from the building via their own heat pump into a common water loop ("HP" in Figure 7-1). This heat can be extracted by the heat pump (not a GSHP exchanging heat with the ground, but a heat pump exchanging heat with the carrier fluid in the loop) in another building for the heating demand in the second building. This is similar to how air conditioning zoning works in commercial systems. In this extreme (and rare) scenario, the thermal load required between both buildings can balance each other and does not require the use of the GSHP to extract or reject energy from the ground, i.e. the buildings can indirectly meet the heating and cooling demands of each other. Most other times, the thermal energy available in the common water loop is not enough to meet the entire thermal demand for the district system. In this case, the additional thermal energy is extracted (or rejected) from (or to) the ground via the common GSHP and ground heat exchangers (GHEs). If needed, further auxiliary thermal energy is available from top-up conventional systems (ASHP). It has been reported that the highest savings occur when a heating and cooling dominant buildings are combined [100]. This will lead to a reduction in GSHP system capacity and GHE length required, which will further decrease the capital costs of the system, increasing the financial feasibility of utilising GSHP systems technology.

For these reasons, research and development of DGSHP systems have been gaining traction over the last five years or so. Mikhaylova et al. [98] described that DGSHP systems have lower normalised costs per energy provided and payback period compared to individual GSHP systems. Alavy et al. [100] further suggested that the average potential financial savings increase with the increase in the number of buildings to be combined. Other authors have investigated and quantified the potential

savings of DGSHP systems applied in Japan, UK, Czech Republic, Italy and Germany for various district sizes [39, 115, 182-187]. Furthermore, with the recent uptake of studies for using geo-structures as an energy source (such as via tunnel linings, e.g. [123, 188, 189]), there has been a further investigation for providing DGSHP systems along the alignment of such structures. Such research has been performed for London's Cross Rail Tunnel studies [122, 123], and for an extension of an underground railway in Torino, Italy [121]. However, experimental field performance data of DGSHP systems are still limited. One example of such limited data is the field monitoring data collected at Ball State University in the USA, with an average yearly efficiency of 3.74 [190]. Environmental benefits of district systems have not been widely discussed in the present literature.

Despite all these previous studies, there has been limited evidence of DGSHP system studies in Australia. There is some potential for the adoption of DGSHP systems in Australia, specifically under temperate climate conditions, such as the ones encountered in Melbourne, where most commercial buildings are cooling dominant and can be combined with heating dominant residential buildings. This mix use case is often found in high rise buildings where the lower floors are often for commercial use (e.g., offices) while the higher floors are often for residential use (e.g., apartments). This chapter considers both heating and cooling needs of a building, unlike previous district study by Mikhaylova et al. [98] who only considered heating needs.

Furthermore, the investigation of DGSHP systems in Melbourne climatic conditions is particularly relevant because there has been a plan for several large infrastructure developments with the potential to use such systems. The examples of such projects are the Melbourne Metro Tunnel project, Western Distributor Tunnel Project and Fishermans Bend area development (the largest urban redevelopment project in the country). In this chapter, different building types with varying thermal loads are used to represent a real district, exemplified by combinations of residential, commercial and sport centre buildings. Therefore, this leads to the study conducted in this chapter, with the aim to provide decision makers with information based on a sound and objective methodology which may allow further pilot trials in one of these big projects.

In this chapter, the financial feasibility of DGSHP systems under Melbourne climatic condition was investigated by comparing the costs between individual and district GSHP systems to install, replace (if necessary) and operate the system for 20 years life span. Firstly, the possibility to combine different residential buildings with different occupancy patterns were investigated. In the second part of the chapter, a more extreme example of DGSHP systems was considered, where different buildings with various load patterns were combined. Further investigation was conducted regarding the number of buildings to be combined in the district arrangement. Finally, the lifetime emissions between individual and district systems are briefly compared.

7.3 Methodology

The methodology used in this chapter builds upon the analysis presented in Aditya et al. (2019) and used in previous chapters, where the total normalised cost (TNC) per unit of thermal energy was calculated for individual buildings. In this chapter, the algorithm is extended to account for multiple buildings and described below. The algorithm used in this chapter is provided in Appendix C and implemented using Python.

7.3.1 Load sharing in DGSHP systems

In the first part of the chapter, a DGSHP system is considered for a collection of residential units/dwellings, such as in an apartment block or on a master-planned estate. In this case, the individual dwellings are similar to each other, including their heating and cooling systems. One factor that is not typically accounted for during these heating and cooling system design process is the occupancy pattern of the occupiers. For example, a typical apartment building can be occupied by users with different occupations and demographics, such as a full-time worker, a retiree and a family with young children. These different occupancy pattern results in different heating and cooling requirement because the heating and cooling system is normally switched off when the occupier is not at home. This means that in a DGSHP system configuration, some occupiers can utilise the installed common GHE fields while some other occupiers may be away. This is expected to reduce the total GHE length required to satisfy the bulk thermal demand in all buildings and hence, lower capital costs overall.

Previously, Ren et al. [191] conducted a study where they simulated household energy consumption based on data from a national survey "*How Australians use their time*". Based on this study, five occupancy patterns were adapted to reflect whether the occupants are at home or away. These five occupancy patterns (OP1 to OP5) are:

- Occupancy pattern 1: A full-time worker who is away from 9 AM to 5 PM;
- Occupancy pattern 2: A retiree who is always at home;
- Occupancy pattern 3: A morning part-time worker who is away from 9 AM to 1 PM;
- Occupancy pattern 4: An afternoon part-time worker who is away from 1 PM to 5 PM;
- Occupancy pattern 5: Full-time worker with a child where the child returns home early from school, so the dwelling is empty from 9 AM to 3 PM.

For simplicity, these occupancy patterns were assumed for 7 days a week. In reality, these occupancy patterns may be different for typical weekends usage but can be relatively similar. For example, OP3 might reflect the typical occupancy pattern for a property owner who goes out for breakfast on a weekend day. Overall, the 5 occupancy patterns for a full 7 day week are shown in Figure 7-2, where an occupancy factor value of 0 reflects that a property owner is away, and a value of 1 means the property owner is at home and using the heating and cooling systems.

Based on these relevant occupancy patterns, the hourly thermal demand for the individual dwelling can be calculated through the bin method described in IGSHPA [10] and by using the weather data gathered from Meteonorm [146]. A thermal load of 0 kW is assumed when the occupants are away, whereas when the occupants are present, a varying thermal load is needed, based on the outside air temperature. The amount of heating and cooling needed is correlated with the air temperature variation away from the balance point, which is assumed as 17.5 °C in this work. For simplicity, the maximum thermal load is assumed to be 10 kW in Melbourne and this occurs when the outside air temperature is at the highest or the lowest point (i.e., hottest day of the year requires 10 kW of cooling). The conversion from the outside air temperature into thermal load was conducted in Python, where the algorithm has been included in Appendix C.

This individual thermal load pattern is used to represent 5 different possible types of dwellings, i.e. Dwelling type 1 with occupancy pattern 1 up to Dwelling type 5 with occupancy pattern 5. Individually, they have a hybrid GSHP system installed. Alternatively, they can also be a part of a larger district GSHP system.

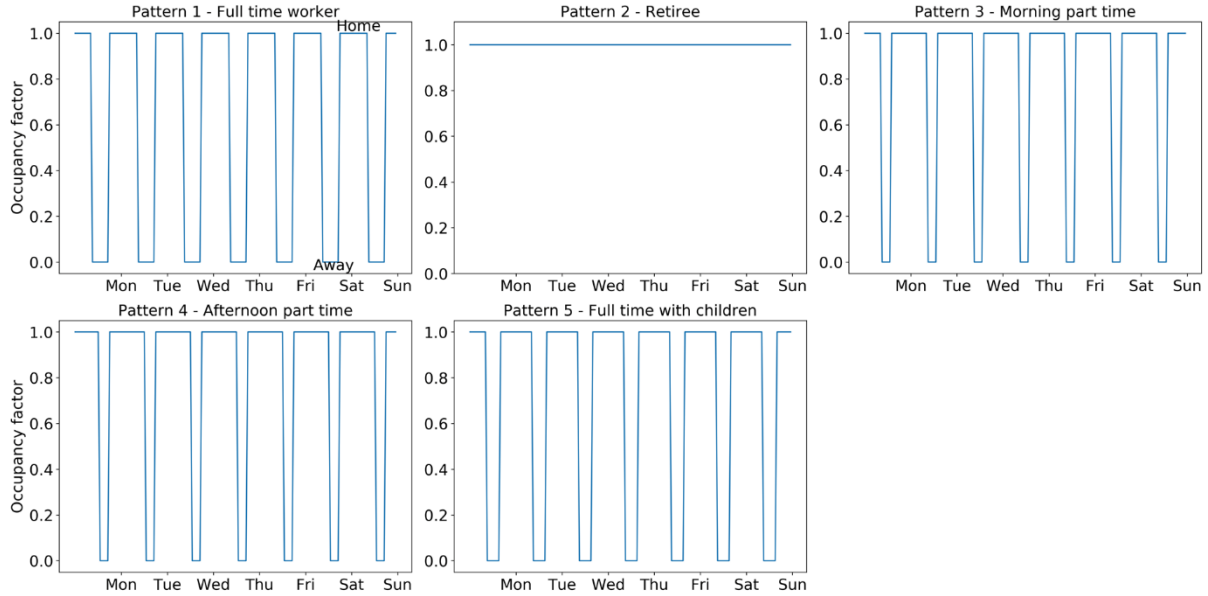


Figure 7-2: Five different occupancy patterns (OPs) considered in this chapter. A value of 0 represents the dwelling is unoccupied (and the HVAC system off) and a value of 1 represents that the dwelling is occupied (and HVAC system on).

A hybrid GSHP (HGSHP) system is one where a GSHP system is sized to provide baseload thermal energy for a building and supported by a conventional system during the hottest and coldest days of the year. The proportion of total heating and cooling loads provided by a GSHP system and a conventional system is called a *shave factor*. In this chapter, the shave factors are varied from 0% to 100% with a step size of 2% to cover a range of configurations. ASHP is chosen to represent the top-up conventional system for simplicity because it can be used to provide both heating and cooling, and also one of the most popular conventional systems used in Australia [1]. An HGSHP system with 0% shave factors is essentially an ASHP system, while an HGSHP with 100% shave factors is essentially a GSHP system. A shave factor of 60% means the GSHP system provides 60% of the peak load, while the ASHP system provides the remaining 40%.

The GHE lengths (L_{GHE}) component of the GSHP and HGSHP systems can be calculated next. L_{GHE} is derived from a function of peak hourly ground load (q_h), peak monthly ground load (q_m) and average yearly ground load (q_y). The ASHRAE design equation, shown as Equation (15) is used to compute this [60].

$$L_{GHE} = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{\frac{(T_i + T_o)}{2} - (T_g + T_p)} \quad (15)$$

where R_b is the effective thermal resistance of the borehole and calculated based on the methodology used by Philippe et al. [60]. R_{10y} , R_{1m} , R_{6h} are the effective thermal resistance of the ground to 10 years, 1 month and 6 hours of ground load respectively. They are calculated by using the cylindrical heat source solution by Carslaw and Jaeger [50] in respective to the relevant time frame (6 hours, 1 month or 10 years). T_i and T_o are the inlet and outlet temperature to the GSHP (or EWT and LWT respectively: entering and leaving water temperatures), T_g is the ground temperature and T_p is the temperature penalty (assumed as 0 for a single GHE or GHEs sufficiently apart from each other, $\sim >6m$). The relevant parameters used for the calculation of L_{GHE} are provided in Table 7-1.

Table 7-1: Parameters used for sizing of GHEs

Design parameter (units)	Description	Value
q_h, q_m, q_y (kW)	Peak hourly, monthly average and yearly average ground loads	Calculated based on building thermal demand, heating and cooling shave factors, and COP of GSHP
R_b (m.K/W)	Effective thermal resistance of the borehole	0.103
λ (W/m.K)	Ground thermal conductivity. It is used to calculate R_{6h} , R_{1m} and R_{10y}	2.5
R_{6h} (m.K/W)	Effective thermal resistance of the ground to 6 hours of ground load	0.106
R_{1m} (m.K/W)	Effective thermal resistance of the ground to 1 month of ground load	0.146
R_{10y} (m.K/W)	Effective thermal resistance of the ground to 10 years of ground load	0.153
T_g (°C)	Undisturbed ground temperature at shallow depths	16.5
$T_{i,h}$ (°C)	Inlet temperature to GSHP in heating operation	$T_g - 5.5$ °C ($T_g - 10$ °F)
$T_{i,c}$ (°C)	Inlet temperature to GSHP in cooling operation	$T_g + 11.1$ °C ($T_g + 20$ °F)
T_p (°C)	Temperature penalty	0 (GHE is thermally independent)

An example of the effect of these occupancy patterns on the thermal load demand and L_{GHE} for a one-week summer period is presented in Figure 7-3. This plot presents a comparison of a typical heating and cooling usage between a full-time worker (OP1) and a retiree (OP2). The occupancy pattern of the retiree is effectively the typical heating and cooling usage without considering any occupancy factors and represents the standard design method for GSHP systems. It can be observed that because the occupants with full-time jobs are away during the day, this thermal load pattern has slightly lower peak load (in this case in cooling usage), and significantly less total thermal energy demand throughout the week than that of a retiree. Therefore, dwellings with this full-time worker's load pattern would need a slightly shorter GHE length. In this case, the calculated GHE design length for a 10 kW GSHP systems for a standard unit with a full-time worker's and a retiree's occupancy patterns are 287 m and 304 m respectively.

For the district configuration, several occupancy pattern combinations were considered:

- District serving dwellings with 2 occupancy patterns (e.g. OP1 and OP2, OP1 and OP3, etc.)¹;
- District serving dwellings with 3 occupancy patterns (e.g. OP1, OP2 and OP3); and
- District serving dwellings with 4 occupancy patterns (e.g. OP1, OP2, OP3 and OP4)

These combinations are illustrated in Figure 7-4 and only unique permutations are considered. For example, a combination of OP1 and OP2 is the same as a combination of OP2 and OP1, so only one of them is considered in the analysis. In total, 120 possible unique districts are investigated, including combinations of two, three or four dwellings, where applicable, along with their respective unique occupancy patterns.

¹ In other words, in general, 50% of the units in the district has an occupancy pattern and the other 50% has another pattern of use. However, this configuration also includes the case where all units have the same usage pattern (i.e., OP1 + OP1)

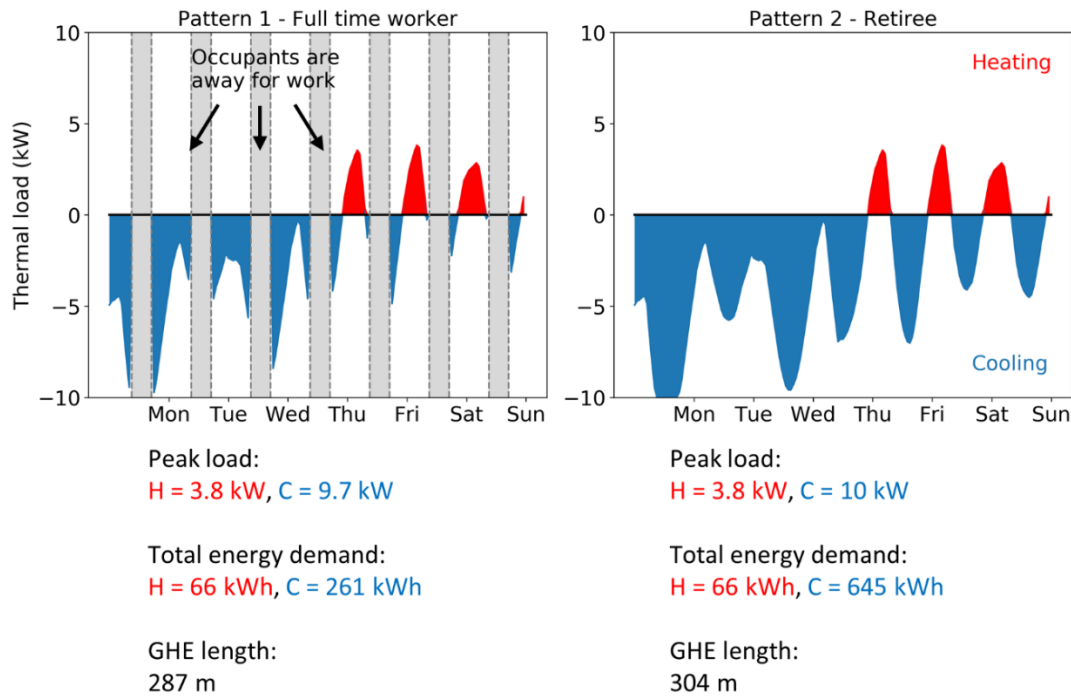


Figure 7-3: Thermal load comparison between dwellings with a full-time worker and a retiree for a typical 10 kW unit in Melbourne

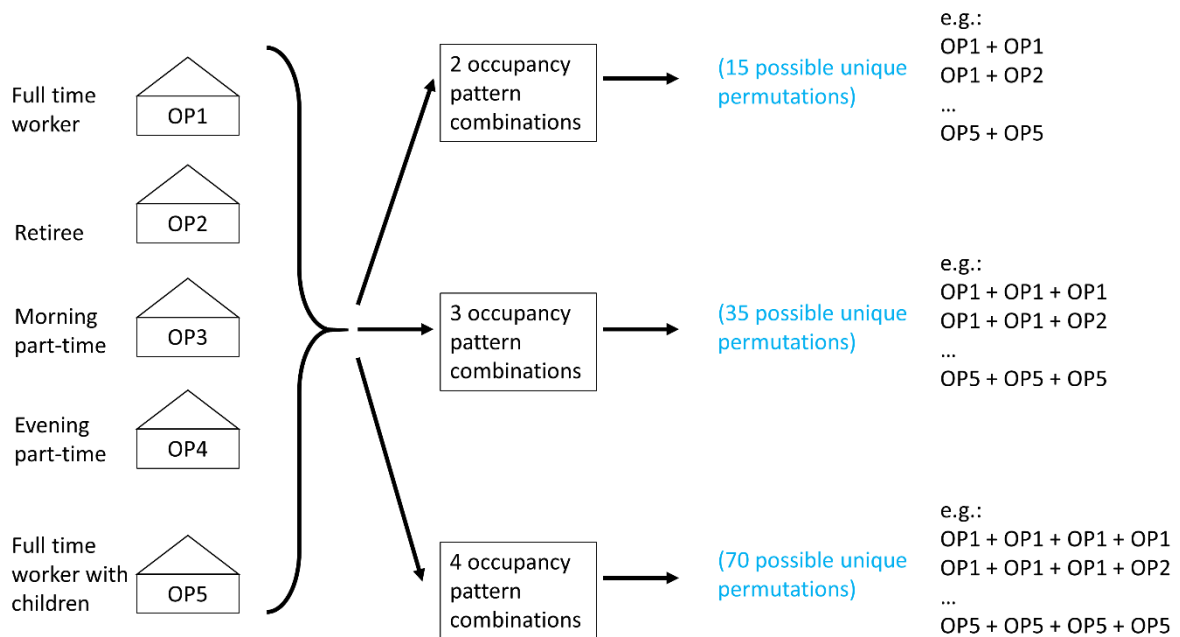


Figure 7-4: Illustration of different dwelling combinations to represent different occupancy pattern combinations considered

An economic parameter is utilised in this analysis to compare the potential financial benefits when the dwellings have their HGSHS systems installed individually or combined in a district arrangement. The calculation is conducted in Python and using the algorithms shown in Appendix D. The chosen financial parameter is the total normalised cost (TNC), shown in Equation (16), where TNC (in A\$/MWh) is the ratio between the net present costs (NPC) and the total thermal energy provided by the system. This TNC indicates the NPC required to provide 1 MWh of thermal energy. The NPC includes all cash outflow to account for installation, replacement (if required) and operation of the heating and cooling systems, discounted at a discount rate r . Moreover, normalising the NPC by the

total thermal energy provided allows a fair comparison as each of the occupancy pattern scenarios has a different total thermal energy demand.

$$TNC = \frac{NPC}{\text{Total thermal energy provided by the system}} \quad (16)$$

The financial parameters and assumptions used are based on the work by Lu et al. [41] and summarised in Table 7-2 below. One of the main assumptions used is the life span of a GSHP and ASHP system as 20 and 10 years respectively, which means that the ASHP needs to be replaced once at the half-way point. The replacement costs are assumed to be the same as the original cost. It is also further assumed that maintenance costs are similar in both configurations, although district arrangements are expected to benefit from economies of scales, but this is not accounted for here for simplicity. The analysis is presented in Australian dollars (A\$) and one A\$ is approximately US\$ 0.72 at the time of writing.

Table 7-2: Parameters assumed for cost and environmental comparisons (based on [41] and [47])

Parameter (units)	Value	Note
Cost of drilling (A\$/m)	80	Borehole installation
Cost of GSHP (A\$/kW)	2,000	Equipment and installation of the system
Cost of ASHP (A\$/kW)	1,000	Equipment and installation of the system
Emissions for drilling (kgCO ₂ e/m)	7.8	Including HDPE pipes, drilling and grouting
Emissions for GSHP and RCAC unit (kgCO ₂ e/kW)	69	Including material and manufacturing
Electricity inflation rate (%)	6.2	
Discount rate, r (%)	3.5	
Life span of GSHP system (years)	20	
Life span of ASHP system (years)	10	
Replacement of ASHP system	Every 10 years	
Design life (years)	20	
Electricity price (c/kWh)	27.6	Based on typical price from an energy retailer [192]
Electricity emission factor (kgCO ₂ e/kWh)	1.08	Based on Department of Environment [127]

With the above methodology, the TNCs were calculated for each of the dwellings with their own unique occupancy pattern, as well as for all possible unique district combinations. Following this, the TNC ratio between the district and individual arrangement was calculated. For example, for cases with two occupancy patterns combinations, by using Equation (17):

$$TNC \text{ ratio} = \frac{TNC_{i+j}}{TNC_i + TNC_j} \quad (17)$$

where TNC_{i+j} indicates the TNC of districts serving dwellings with OP_i and OP_j. TNC_i and TNC_j refer to a standalone system which describes the TNC of the individual Dwellings with a use pattern OP_i and Dwellings with OP_j individually (and i,j =1,...,5). This ratio can be used to indicate if there exist any financial benefits from utilising DGSHP systems compared to individual HGSHP systems. Because of the load sharing nature in district arrangement, it can be assumed that this saving ratio is always lower than 1.

Further comparisons for the lifetime carbon emissions between the district and individual systems are also provided. The lifetime emissions are the sum of the initial emissions (related to the installation of the system and including the manufacturing of the heat pump and drilling of GHEs) and the emissions generated annually from operating the heating and cooling systems [47, 171]. The relevant parameters used for environmental analysis are included in Table 7-2. It should be noted that the electricity emission factor in Melbourne of 1.08 kgCO₂e/kWh is extremely high, but this is because the local electricity fuel mix is dominated by coal [127].

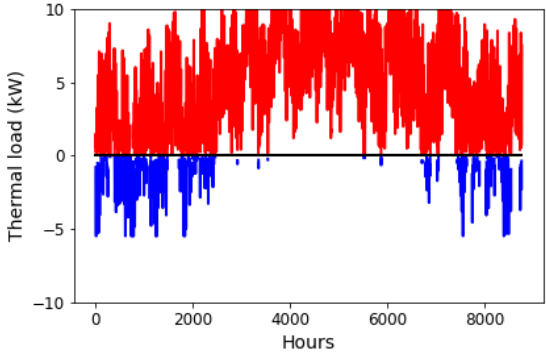
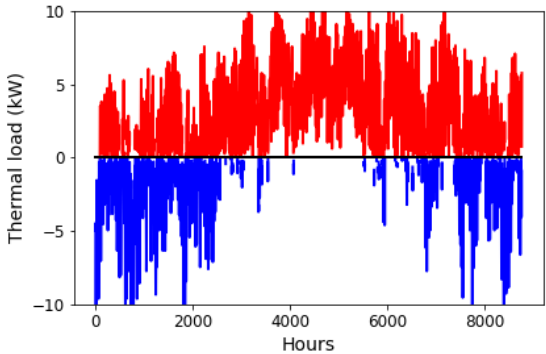
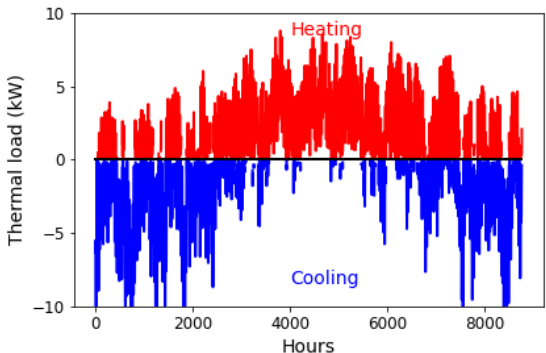
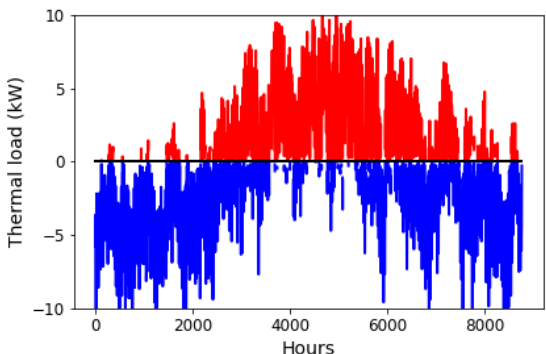
7.3.2 Load pooling in DGSHP systems

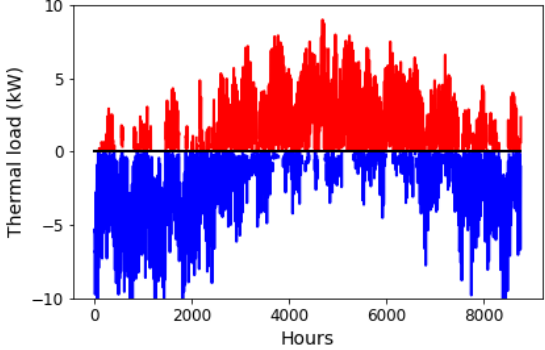
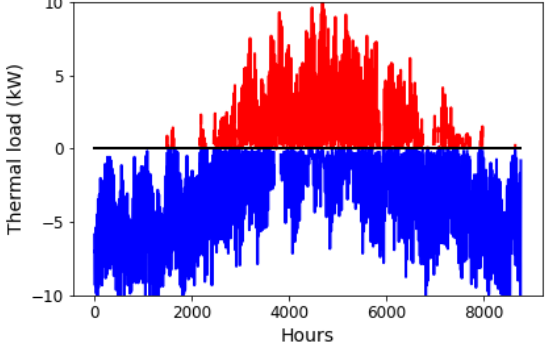
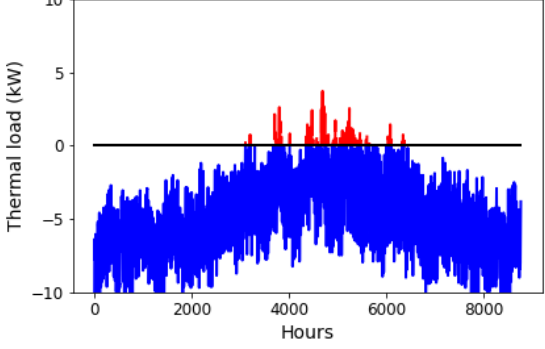
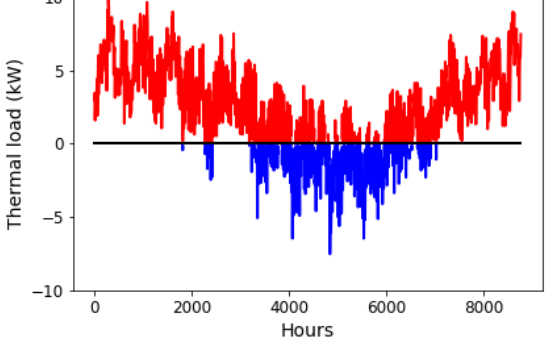
The first part of this chapter considered the load sharing benefits of DGSHP systems. In this case, when one building needs heating, the other building also needs heating (if the occupant is present). The buildings have very similar thermal load pattern, where the occupancy patterns only determine whether the occupants are present or not. Furthermore, all the occupants stay at home throughout the night in all of the occupancy patterns considered, which may limit the benefits of DGSHP systems.

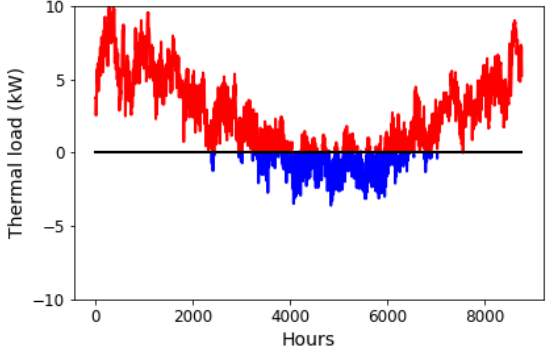
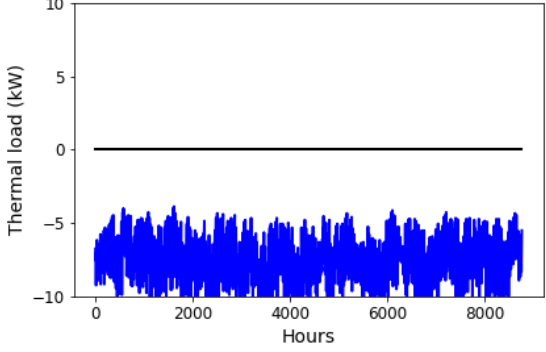
In the second part of this chapter, the load pooling ability between buildings was investigated. To do this, different buildings need to have significantly different load patterns, which is often the case for buildings with different types of usage, such as residential, retail, commercial, swimming pool centre and data centre. It is envisioned for the ideal scenario where a building that needs 5 kW heating can extract the thermal energy from a common water loop, containing energy rejected from a nearby building that needs 5 kW cooling. A possible real-life example here is the heat rejected from cooling a data centre can be used to heat a swimming pool nearby. In this scenario, heat exchange occurs between the buildings in a closed system. If there are any load imbalances, then supplemental thermal energy can be extracted or rejected to the ground through a GSHP system. If needed, this system can be further supported by conventional systems, such as ASHP.

To do this, 10 different thermal load patterns were selected to represent possible different heating and cooling system usage under Melbourne climatic conditions. These different thermal load patterns are presented in Table 7-3, along with the user behaviour types that they might represent and their total annual heating and cooling thermal demand. Different usage patterns were considered here, where some patterns are heating and some are cooling dominant. One pattern (TL5) to represent a relatively balanced heating and cooling requirement was also included. For simplicity, this section assumes heating and cooling are present all year round, where the occupancy pattern presented earlier in Section 7.3.1 (occupants or away or present) was not considered.

Table 7-3: Thermal load patterns representing different possible heating and cooling usage patterns for a normalised 10 kW buildings in Melbourne

Description	Thermal load pattern	Annual thermal demand (MWh)
<p>TL1: Thermal load pattern to represent typical usage of a sports centre with a swimming pool. Mostly heating usage throughout the year and additional cooling needed during summer.</p>		<p>Heating: 42.8 Cooling: 2.3</p> <p><u>Heating dominant</u></p>
<p>TL2: Thermal load pattern to represent typical usage of a residential house. Mostly heating usage and some cooling usage throughout the day during summer</p>		<p>Heating: 26.1 Cooling: 7.8</p> <p><u>Heating dominant</u></p>
<p>TL3: Thermal load pattern to represent typical usage of a residential house. This house utilises different temperature setpoint than TL2, where the occupants prefer that the house remains slightly cooler throughout the year</p>		<p>Heating: 16.0 Cooling: 11.5</p> <p><u>Heating dominant</u></p>
<p>TL4: Thermal load pattern to represent typical usage of a residential house. This house utilises different temperature setpoint than TL2, where the occupants prefer that the house remains significantly cooler throughout the year</p>		<p>Heating: 13.5 Cooling: 18.5</p> <p><u>Cooling dominant</u></p>

Description	Thermal load pattern	Annual thermal demand (MWh)
<p>TL5: Thermal load pattern to represent typical usage of a residential house. This house utilises different temperature setpoint than TL2, where the occupants prefer that the house has moderate temperature all the year round, with relatively balanced heating and cooling need</p>		<p>Heating: 12.3 Cooling: 14.6</p> <p><u>Cooling dominant, but relatively balanced</u></p>
<p>TL6: Thermal load pattern to represent typical usage of an office. Significant cooling usage throughout the year, with some heating usage during the winter</p>		<p>Heating: 8.0 Cooling: 29.0</p> <p><u>Cooling dominant</u></p>
<p>TL7: Thermal load pattern to represent typical usage of a large gym. Significant cooling usage throughout the year to meet high occupancy with intense physical activities. Limited heating usage during the winter</p>		<p>Heating: 0.2 Cooling: 42.2</p> <p><u>Cooling dominant</u></p>
<p>TL8: Thermal load pattern to represent significant hot water usage throughout the year and also requires some cooling for a large freezer. It represents a thermal usage of a research institution or a hospital</p>		<p>Heating: 24.3 Cooling: 3.5</p> <p><u>Heating dominant</u></p>

Description	Thermal load pattern	Annual thermal demand (MWh)
<p>TL9: A similar pattern to TL8, but TL9 has less thermal variation throughout the year</p>		<p>Heating: 23.9 Cooling: 2.4</p> <p><u>Heating dominant</u></p>
<p>TL10: Thermal load pattern to represent significant cooling usage throughout the year, such as for a data centre or an ice-skating rink</p>		<p>Heating: 0 Cooling: 64.6</p>

Similar to the last section, these 10 heating and cooling thermal load patterns (shown in Table 7-3) were investigated in both district and individual arrangements, both from financial and environmental perspectives. Different permutations of two, three or four of these thermal load pattern combinations were considered as before. For simplicity, it is assumed that those buildings are located next to each other and hence, the thermal loss is minimised when thermal energy is exchanged between the buildings. The energy can be exchanged through the pipe networks which connect both the heat pumps in each building. This is an idealised scenario and this thermal loss between buildings need to be considered in future works since if the distance between the buildings increases, then some heat loss will occur as the thermal energy are transported between them.

It is hypothesised that the highest benefit will occur when a heating dominant building is combined with a cooling dominant building. It is important to recognise that this idealised scenario is rare and unlikely to be encountered in real life. If there is, most likely these buildings will not be co-located, which raises other limitation such as the spatial distribution of buildings. The most probable real scenario accounting for this heating dominant-cooling dominant collocated uses/buildings, might be a sport centre, where there is a gym that most likely requires cooling throughout the year and a swimming pool which most likely requires heating throughout the year.

7.4 Results and discussions

The methodology described above was used to calculate various thermal loads for Melbourne climatic conditions. The first part of the results presents the load sharing benefits of DGSHP systems based on whether the occupants are away or present. The second part of the results discusses the load pooling benefits of DGSHP systems, where different building types are combined in district arrangements. In this work, 3 different district combinations were considered where two, three or four buildings were combined in district arrangement. Up to 4 building combinations were considered to minimise the computational time, especially considering the potential unique permutations available. The computation was conducted in Python using the algorithms presented in Appendix C.

7.4.1 Load sharing comparison between hybrid GSHP and DGSHP systems

Based on the methodology presented above, the lowest TNCs for an individual dwelling (Dwelling 1 to 5), with the occupancy patterns shown earlier in Figure 7-2, were calculated and the results are presented in Table 7-4. In Table 7-4, the lowest TNC represents the most cost-efficient hybrid system combination to provide 1 MWh of thermal energy for each occupancy pattern. For example, the lowest TNC HGSH system demand for a full-time worker under Melbourne climatic conditions would cost A\$178/MWh to install and operate the system. With this configuration, 180 m of GHE is needed and the geothermal portion can provide heating and cooling demand for around 77% of the year, while the rest is supported by a conventional ASHP system.

The longest GHE length requirement is for the dwelling designed for a retiree, with the heating and cooling system running for the entire year. This scenario also represents the design with the highest normalised cost to install and run the system for 20 years. In contrast, the lowest GHE length requirement occurs for the house for a full-time worker, where it is assumed that the occupants are away the most, and hence utilise the least heating and cooling.

Table 7-4: Summary of the lowest TNCs for 5 dwellings with 5 occupancy patterns considered

Occupancy pattern (OP)	Description	Lowest TNC (A\$/MWh)	GHE length (m)	Total thermal demand provided by GSHP systems (%)
1	A full-time worker	178	180	77
2	A retiree	154	231	89
3	A morning part-time worker	165	208	85
4	An evening part-time worker	166	196	81
5	A full-time worker with children	171	190	80

The next step is to calculate the lowest TNCs for combinations of these dwellings in district arrangements. These lowest TNCs for each district combination can be compared to the relevant TNCs for individual arrangements (as per Table 7-4) by calculating their TNC ratio. These TNC ratios are presented in Figure 7-5, along with the minimum, mean and maximum TNC ratio, as well as their probability density function (PDF), which is represented by the curve around the vertical lines. It can be observed that the district systems can reduce TNC by just about 2% compared to the individual systems for the combinations of 2, 3 or 4 occupancy patterns. A TNC ratio of 1 represents combinations of dwellings with the same occupancy pattern. For example, a district system with 3 combinations of Dwelling 1 will perform similar to 3 times of Dwelling 1 individually, hence a TNC ratio of 1 where there are no financial savings realised. Furthermore, the PDF curve reveals that for 2 occupancy pattern combinations, most of the TNC ratios are located near the top (TNC ratio of 1). As more dwellings with different occupancy patterns are combined, the peak of the density distribution curve starts to shift downward, which means that combining more dwellings with different occupancy patterns can yield higher financial savings. This is also supported with the fact that as more dwellings are combined, the average TNC ratio decreases, where the mean TNC ratio are 0.996, 0.995 and 0.994 for a combination of 2, 3 and 4 dwelling types, respectively.

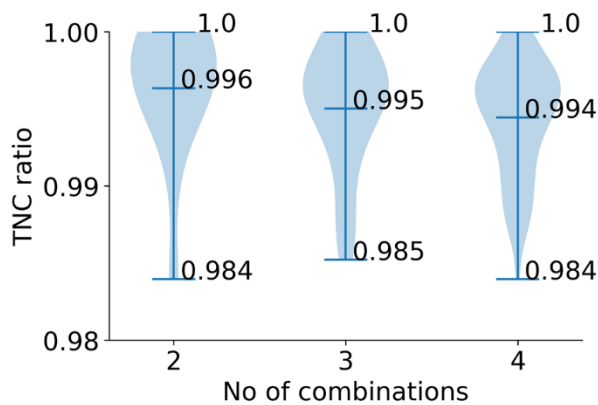


Figure 7-5: TNC ratios for 2, 3 and 4 dwelling combinations using occupancy patterns 1 to 5. The probability density function, minimum, mean and maximum TNC ratio for each dwelling combination are also provided

The occupancy pattern combinations that yield the highest TNC savings ratio (i.e. lowest TNC ratio) for each occupancy pattern combination is presented in Table 7-5, where the lowest TNC ratios are between 0.984 and 0.985 for all combinations. The highest savings occur for combinations associated with occupancy pattern 1 and 2. This combination represents the two with the most contrasting occupancy patterns: occupancy pattern 1 (full-time worker) represents the pattern with the highest proportion that the occupier is away from home, whereas occupancy pattern 2 (retiree) represents a pattern that the occupier is always at home.

From Table 7-5, it can be observed that the GSHP systems in district arrangement have slightly lower GHE length requirements than that of individual arrangement. The lower GHE length required translates into lower capital costs to install the system. The GSHP components in these district arrangements can satisfy about 80% thermal demand, which is slightly lower compared to the (optimised hybrid) individual arrangement. This means that, compared to the individual systems, the district systems require slightly more usage of conventional systems (ASHP is assumed here). The ASHP systems have lower efficiency that results in more electrical energy consumed, which in turns resulted in slightly higher annual operating costs and carbon emissions. Overall, the savings in GHE length in the DGSHP systems is slightly more than the additional annual operating costs, hence the slightly lower estimated TNCs in DGSHP systems compared to individual GSHP systems.

The results presented in Table 7-5 indicate that district systems yield no environmental benefit compared to individual systems under the occupancy patterns with the lowest TNC ratio. Under this thermal load combination, a DGSHP system emits slightly higher lifetime emissions compared to individual GSHP systems. This higher emissions are generated due to more frequent ASHP systems operation throughout the year. A less efficient ASHP requires more electricity to run the system, which in turn increases the annual carbon emissions.

It is also important to recognise that adding more buildings do not generate significant additional savings for the scenario presented here. In fact, the DGSHP systems with the lowest TNC for 4 occupancy pattern combinations is the same as two times of the lowest TNC for 2 occupancy pattern with the same combinations. This result is mainly because the thermal load patterns consider in this scenario is fairly similar. The analysis conducted in this section is limited by the occupancy patterns of the occupants. Changing their behaviour pattern would also change the results of this analysis. Therefore, a more realistic result is expected if the analysis is repeated with different thermal load patterns such as in Section 7.4.2.

Table 7-5: Summary of the lowest TNC ratio between district and individual arrangements for different occupancy pattern combinations

Variables	2 combinations		3 combinations		4 combinations	
	District set-up	Individual set-up	District set-up	Individual set-up	District set-up	Individual set-up
Description	OP1+OP2		OP1+OP2+OP2		OP1+OP1+OP2+OP2	
GHE length (m)	379	411	595	641	759	822
Total thermal demand provided by GSHP systems (%)	81	83	83	85	81	83
Capital costs (A\$)	70,342	72,867	107,597	111,309	140,684	145,737
Operating costs (A\$/year)	4,402	4,329	6,917	6,818	8,804	8,657
TNC (A\$/MWh)	163	166	159	162	163	166
TNC ratio	0.984		0.985		0.984	
Carbon emissions (ton CO ₂ e/year)	17.2	16.9	27.1	26.7	34.5	33.9
Lifetime emissions (ton CO ₂ e)	349.4	343.8	548.8	541.3	698.8	687.7
Lifetime emission ratio	1.016		1.014		1.016	

The results presented above seems to indicate that although limited, there are some potential financial savings for DGSHP systems. More savings can be realised when dwellings with significantly different usage patterns are combined in the district arrangement. However, the analyses presented here have only considered the benefits of load sharing in DGSHP systems. In this case, when one dwelling needs heating, the other dwelling also needs heating (if the occupant is present). In a district system, it is possible that when one dwelling needs heating, a nearby dwelling needs cooling instead. This will be discussed in the next section.

7.4.2 Load pooling comparison between hybrid GSHP and DGSHP systems

In this section, the load pooling benefit of DGSHP systems is investigated. This benefit only occurs when the buildings that are combined in district arrangement have different thermal load patterns. It is envisioned that when a building needs 5 kW heating, it can extract the thermal energy from a common water loop, containing energy rejected from a nearby building that needs 5 kW cooling. A possible real-life example here is the heat rejected from cooling a data centre can be used to heat a swimming pool nearby. In this scenario, heat exchange occurs between buildings in a closed system on the load side. If there are any load imbalances, then supplemental thermal energy can be extracted (or rejected) from (or to) the ground through GSHP system.

Similar to the previous section, the 10 heating and cooling demand patterns, shown in Table 7-3, are investigated in both district and individual arrangements, both from financial and environmental perspectives. Different permutations of 2, 3 or 4 of these thermal load pattern combinations were considered. It is further expected that the highest benefit will occur when a heating dominant building is combined with a cooling dominant building. An example of this situation is provided in Figure 7-6, where a heating dominant thermal load pattern for a swimming pool (TL1) is considered in district arrangement with a cooling dominant thermal load pattern for a data centre (TL10).

The illustration in Figure 7-6 presents the thermal pooling possibilities when heating and cooling dominant buildings are combined in district arrangement. In the individual arrangement, significant thermal energy imbalances need to be extracted from or rejected to the ground, and this requires very long GHEs, which is approximately 400 m each, in both TL1 and TL10 scenarios presented. In the district arrangement, some of this energy can be firstly used to heat or cool the other building, and if there is excess energy, then GSHP is used to extract or reject energy to the ground via GHEs. For example, the cooling dominant building with TL10 pattern significantly rejects thermal energy to the common water loop, which increases the temperature in both the common water loop and the storage water tank. Some of this thermal energy can be used to heat the significantly heating dominant building with TL1 load pattern. The excess energy (37.3 MWh over the whole year) is rejected to or extracted from the ground using standard GSHP systems operating procedures. Effectively, 72.4 MWh (36.2 MWh for each building) is exchanged between these buildings without the need to reject or extract energy from the ground.

One of the most significant implications of the district arrangement above is the reduction of the GHE length requirement. For the individual buildings presented in Figure 7-6, the required GHE lengths are 408 and 410 m. Combining this building in district arrangement has slightly increased the peak load of the buildings. However, the thermal energy that needs to be extracted or rejected to the ground has decreased significantly. Therefore, these buildings now require less total GHE length (376 m), which is less than half of the total GHEs needed for both buildings individually (818 m). One additional benefit is that, when buildings having highly unbalanced heating and cooling requirements are combined, the resulting thermal load is less unbalanced, and hence also requires less GHE length as shown in this example.

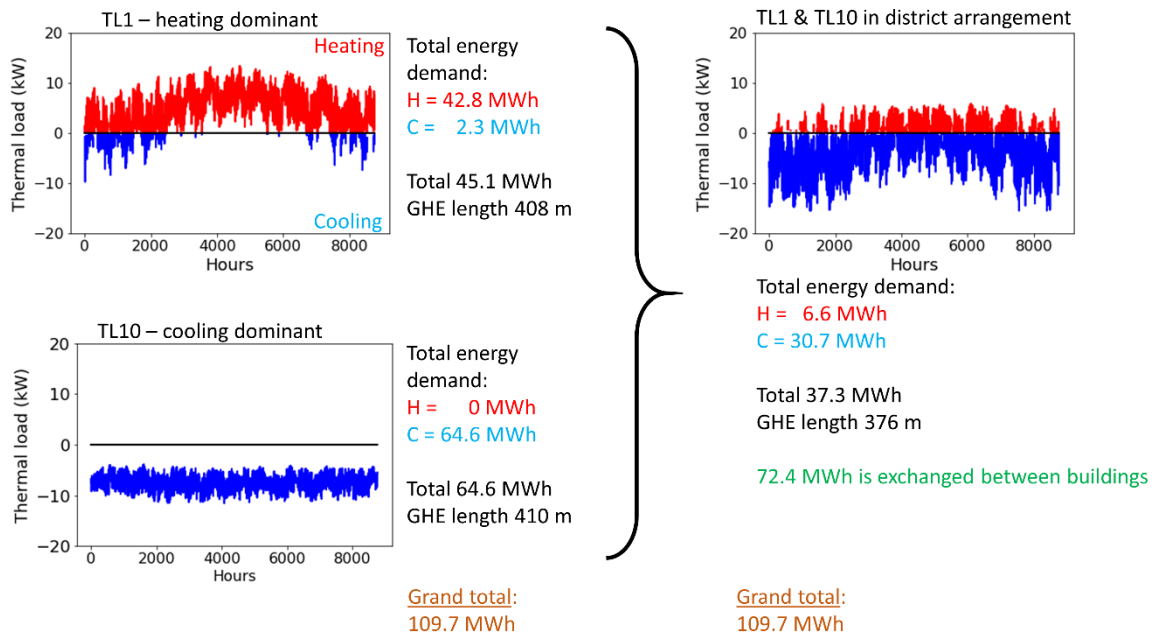


Figure 7-6: Illustration of load pooling between buildings where a heating dominant house is combined with a cooling dominant data centre in district arrangement

The previous analysis is then repeated for every possible permutation for district arrangement with 2, 3 and 4 building combinations, with TL1 to TL10 thermal load patterns shown earlier. The TNC for each of these combinations were calculated to maximise the financial return for the DGSH systems. To investigate the benefit of district arrangement over individual arrangement, the TNC ratios were also calculated, where the results are presented in Figure 7-7 along with the minimum, mean and maximum TNC ratio as well as their PDF. Table 7-6 also presents the configurations with the lowest TNC ratio for the number of building combinations investigated.

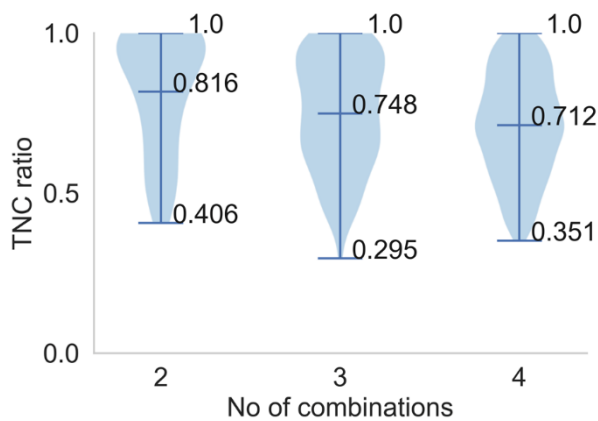


Figure 7-7: TNC ratio for 2, 3 and 4 building combinations using thermal load patterns 1 to 10

Table 7-6: Summary of the lowest TNC ratio between district and individual arrangements for the 10 thermal load patterns considered

Variables	2 combinations		3 combinations		4 combinations	
	District set-up	Individual set-up	District set-up	Individual set-up	District set-up	Individual set-up
Description	TL1 and TL10		TL1, TL9 and TL10		TL1, TL9, TL9 and TL10	
GHE length (m)	228	749	218	924	319	1,099
Total thermal demand provided by GSHP systems (%)	82	97	93	89	84	85
Capital costs (A\$)	49,130	99,906	48,442	133,907	72,128	167,909
Operating costs (A\$/year)	2,855	7,688	2,723	9,798	3,957	11,908
TNC (A\$/MWh)	57	140	44	150	55	156
TNC ratio	0.406		0.295		0.351	
Carbon emissions (ton CO ₂ e/year)	11	30	11	38	15	47
Lifetime emissions (ton CO ₂ e)	227	609	216	777	315	944
Lifetime emission ratio	0.373		0.279		0.333	

Figure 7-7 presents that the lowest TNC ratio generally decreases, as the number of building combinations increases. The TNC ratio of 1 signifies that one thermal load is combined with itself, thus resulting in no financial savings. The PDF also reveals that there are more limited financial savings for 2 building usage combinations, as more of the calculated TNC ratios are distributed close to this ratio of 1. The TNC ratios for each building combinations presented here have a significantly wider range compared to the earlier results discussed in Section 3.1. For example, the result in Figure 7-7 indicates that the TNC ratio for 2 buildings with a different thermal load in a district arrangement can be as low as 0.4, in contrast to a TNC ratio of 0.98 when 2 buildings with similar load patterns are combined (as presented earlier in Figure 7-5). This indicates that combining buildings with more diverse thermal load patterns can lead to significantly more financial and environmental savings.

The lowest TNC ratio occurs when a heating dominant building is combined with a cooling dominant building. In this case, they are generally combinations of buildings with TL1, TL9 and TL10 thermal load patterns. TL1 and TL9 are heating dominant, while TL10 is cooling dominant. It is noteworthy that both the average and lowest TNC ratio levelled off, as the number of building combination increased (see Figure 7-7). This means that the marginal benefit for adding additional thermal load patterns is decreasing, as the number of different thermal load combinations are added.

The standard deviation for the calculated TNC ratio for 2, 3 and 4 house combinations are 0.183, 0.175 and 0.164 A\$/MWh, respectively. This means that, as more buildings are combined, the TNC ratio are more dispersed closer to the mean, represented by the decrease in the standard deviation. This is also represented by the PDF, where for 2 building combinations, the PDF is skewed towards the TNC ratio of 1, suggesting that there is a minimum financial benefit from the district system. In contrast, for 4 building combinations, the PDF appears to be more normally distributed and centred around the mean TNC ratio of 0.712. These two factors indicate that, as more buildings with different thermal loads are combined, it is more likely to see some financial benefits because their thermal load patterns are diversified. This is in line with previous observations by Alavy et al. [100].

The analysis above is conducted with the intent to minimise the lifetime costs. The obtained results are different if the objective of the analysis is to minimise the lifetime emissions. For the same case study, the lowest lifetime emissions would require using the GSHP system as much as possible. This is especially true in a location with a high electricity emission factor such as in Melbourne. For example, the lowest lifetime cost scenario for a district with two thermal load combinations presented earlier in Table 7-6 has the GSHP sized to meet around 40% of the peak cooling load (5.9 kW out of 15.5 kW peak cooling load), but able to satisfy 82% of the annual energy demand. This district system has a TNC ratio of 0.406, but a lifetime emission ratio of 0.373 when compared to the equivalent individual GSHP systems. In contrast, the same district system needs to be equipped with the full 15.5 kW GSHP if the objective is to minimise the lifetime emissions. In this case, the district system has a higher TNC ratio of 0.43 but a lower lifetime emission ratio of 0.343 when compared to the equivalent individual GSHP systems.

It is important to recognise that the results presented above would likely differ for other locations with a lower electricity emission factor compared to Melbourne. In those locations, the annual emissions would become a smaller part of the lifetime emissions. Hence, the initial emissions generated from GHE drilling would be more significant. Accordingly, it is expected that the lowest lifetime emission in this scenario would be a DGSHP system with a combination of GSHP and conventional systems.

Overall, this section has presented the benefit of load pooling when buildings with different thermal load patterns are combined in the district arrangement. However, there are some limitations that have not been accounted for. Firstly, the potential for a thermal loss during storage and transmission between the buildings needs to be considered, especially once the distance between the buildings and the number of buildings combined increases. The simplified GHE design length method used here does not account for this. More accurate simulations, such as by using a commercial software may be able to account for this better.

Secondly, the power consumption of circulation pumps, where it was needed to move the thermal energy to either the storage tank or to the neighbouring building, have not been accounted for. A small circulation pump, operated at medium speed (150 W) all year round, may require around A\$350 per unit under current Melbourne's electricity pricing. For example, for the scenario with the lowest TNC ratio presented in Table 7-6, operating a circulation pump all year round in each building may result in additional total operating cost of around 25%, 39% and 35% for the combinations of 2, 3 and 4 building combinations, respectively. Therefore, the actual financial benefits of DGSHP systems would be lower than the results presented here.

Combining these individual heating and cooling systems into a district arrangement may change the simplified pricing model presented here. DGSHP system may require complex piping connections from the common-loops to individual houses. Furthermore, the DGSHP system may require an additional complex control system, which may not be required in the individual system. These two additional complexities are expected to increase installation and maintenance costs. In contrast, DGSHP system arrangement may have lower installation cost as well. The unit drilling costs per GHEs for 1,000's GHEs in a district are likely much lower than for two GHEs in an individual installation, due to the economies of scale that may be present, such as by utilising a larger and more efficient drilling rig for drilling the GHEs and significantly reducing costs associated with mobilisation of rigs. These cost variations are difficult to account for in a generalised study such as the one presented here and may compensate each other, thus the results presented here still provide meaningful insights.

Finally, it is recommended to also apply a spatial analysis when a real district is considered. The distance between the buildings can vary, and two (or more) buildings with significantly different thermal loads may not be available next to each other in a given district. The space available to install GHEs also needs to be considered. There is more space available to install the GHEs when ten different single-story buildings are combined in a district arrangement compared to the same scenario for a ten-story building.

7.5 Conclusions

This chapter presents a methodology to calculate the potential financial and environmental benefits of district hybrid ground source heat pump (DGSHP) systems. The lifetime costs and emissions of this district system are compared to the combination of individual hybrid GSHP systems. District GSHP systems application are investigated to explore the possibility to combine individual GSHP systems from nearby buildings.

The analysis presents that the highest financial benefit occurs when a heating dominant building is combined with a cooling dominant building. In this case, buildings can indirectly meet the heating and cooling load requirements of each other. This benefits further increase when the number of buildings combined is increased, where the total normalised costs of buildings in district arrangement can be up to three times cheaper than the same building in individual arrangement. By adding more buildings into district systems, the possible thermal load combinations are being diversified. As the thermal loads are more diversified, it is more likely that any possible combinations can yield some financial savings. However, for combinations that have yielded relatively high benefits (e.g. a highly heating combined with a highly cooling dominant building), the effect of adding more buildings will result in diminishing return, because the thermal load has been diversified and only marginal gain can be attained.

Combining multiple buildings into a district system has also been shown to be able to reduce the lifetime greenhouse gas emissions. A district system with a GSHP system installed at every building typically has the lowest lifetime emissions, especially in a location with a high electricity emission factor such as Melbourne, which is used as an example in this study. Overall, the method suggested in this chapter may be used to assess the potential benefits of district GSHP systems. The unique thermal load patterns in each building may be leveraged to significantly reduce the overall thermal demand in a given district location.

However, it is also important to recognise that there are some simplifications on the analysis conducted here. Further assessments regarding thermal loss between buildings, construction costs of the pipe network and the spatial distribution of interconnected buildings need to be considered in future works.

8 Conclusions and future work

The increasing concerns about climate change have led to increasing interest in renewable energy technology such as the ground source heat pump (GSHP) systems. GSHP systems provide heating and cooling to buildings using thermal energy from the ground. This technology is typically more efficient than conventional heating and cooling systems. Hence, adopting this technology is expected to contribute to lower electricity consumptions, carbon emissions as well as the lifetime costs to install and operate the system.

The world has recognised the benefit of GSHP systems, with increasing popularity, especially in Europe and North America. However, the installation of GSHP systems is very limited in Australia, leading to a lack of understanding and performance data of the systems. These factors lead to GSHP systems installation with low efficiency and high capital costs since the systems were not designed and installed properly. Installers may also increase the installation costs to account for their risks. This doctoral works aim to address some of these shortcomings.

The contributions of this thesis focus on 3 main topics: full-scale monitoring of GSHP systems under Australian climatic conditions, the study of hybrid and district GSHP systems. The learnings from this thesis are expected to improve the understanding and adoption of this technology in Australia, which ultimately may help to contribute to minimising the impact of climate change.

8.1 Key findings

A summary of the key findings from each chapter is outlined here. The learnings gathered from monitoring the performance of various GSHP systems installation throughout Melbourne are summarised first. These learnings were used to conduct further study in hybrid and district GSHP systems. More detailed findings from each study can be found on the conclusion section in Chapter 4, 5, 6 and 7.

In chapter 4, the results from a GSHP system monitoring project is presented. GSHP system performances from 10 different buildings are reported, with more than two years of data collected from each of them. Those collected datasets produce the following insights:

- GSHP systems can work relatively well under Melbourne climatic conditions and based on the heating and cooling demand required by each unique occupiers.
- The 10 monitored properties have a coefficient of performance between 2.0 and 4.6 during this 2.5 years of monitoring period.
- One distinct trend is that those systems are used only around 10 to 20% of the year, which is much smaller compared to the expected based on a typical design method.
- Further detail comparisons are conducted for two properties with the lowest (Cheltenham) and highest (Ashburton) system usage.
- The measured data revealed that the demographics of the occupiers can influence the heating and cooling usage patterns. Other factors such as how the thermostat is utilised can have some impact on how much the system is used. All these factors may explain why the system at Ashburton is used significantly more than at Cheltenham.
- The low GSHP system operation at Cheltenham allows the ground temperature to return towards the undisturbed ground temperature, especially during the period when the GSHP system is not used for several consecutive days.

- Finally, it was revealed that even though the systems at Ashburton and Cheltenham have similar efficiency, but the contrasting user behaviour leads to drastically different financial and environmental savings generated by the systems. Despite the system's efficiency, there is no financial saving available if the system is used minimally.

Overall, this monitoring project reveals that GSHP systems can be an alternative heating and cooling option under Melbourne climatic and geological conditions if designed, installed and used properly. However, the low usage of the systems may severely limit the systems' financial and environmental benefits. One potential reason behind this is the temperate climatic conditions in Melbourne, which require minimum heating and cooling. In such a condition, a hybrid combination between GSHP and conventional systems may be preferred to maximise the benefits from both systems. This leads to the study conducted in Chapter 5 and 6, where the financial and environmental viability of hybrid GSHP (HGSHP) systems are investigated. An HGSHP system means a GSHP system that is sized to provide the baseload thermal energy for a building and this system is supported by a conventional system during the hottest and coldest days of the year.

Chapter 5 focuses on the economic comparisons between GSHP and HGSHP systems for 20 years lifetime of the systems. This analytical study is extended to cover different climatic and cost conditions across several Australian cities. This study leads to the following learnings:

- HGSHP systems typically have lower total normalised costs (TNCs – net present costs per thermal energy unit, in \$/MWh) than GSHP or conventional systems. Lower TNCs of up to 12% were observed for various climatic and cost conditions in Australia.
- HGSHP systems have shorter GHE length compared to their GSHP systems counterpart, leading to a lower initial investment cost. This can be attractive to potential users.
- The financial benefits of HGSHP systems can increase or decrease depending on the variables involved.
- Generally, the TNCs are less sensitive to changes in variables that affect capital costs as opposed to operational costs. This is due to the fact that capital cost is usually a small component of the lifetime cost when compared to 20 years worth of operational costs.

In Chapter 6, a multi-objective optimisation method is adopted where HGSHP system is designed by considering both their economic and environmental benefits. The main findings from this chapter include:

- The HGSHP system combinations that are designed to minimise the lifetime costs are often different than the one with the lowest lifetime emissions.
- Factors such as climatic conditions, efficiency of the systems, energy price ratio between electricity and gas, as well as the emission factor ratio between electricity and gas, can affect financial and environmental benefits of HGSHP systems
- When both the economic and environmental benefits are considered, a higher proportion of GSHP systems in the hybrid component is preferred when changes such as an increase in energy price, an increase in the efficiency of GSHP system and a decrease in the emission factor ratio between electricity and gas occur.
- In contrast, a higher proportion of conventional system is preferred when there is an increase in drilling costs or an increase in the efficiency of the conventional system. In such extreme cases, a conventional system may be preferred as the option with the lowest lifetime costs.

Another option to improve the financial viability of the GSHP system is by connecting individual GSHP systems from nearby buildings in a district arrangement. District GSHP (DGSHP) system is possible because buildings are located close to each other in the urban area. The potential benefits of DGSHP systems compared to individual systems are investigated in Chapter 7 and summarised here:

- DGSHP system can reduce capital and operational costs compared to individual GSHP systems.
- The highest financial saving occurs when buildings with contrasting thermal load patterns are combined together, for example, a heating and a cooling dominant building.
- More financial saving can be observed as more buildings are combined, but this follows the law of diminishing returns.
- Combining more buildings lead to the diversification of thermal load. This means that as more buildings are combined, it is more likely that any combinations of these different thermal load patterns are able to yield some financial benefits.

Overall, the GSHP systems performance datasets collected in this thesis, as well as the investigation in hybrid and district GSHP systems, are envisioned to provide information to push the GSHP systems industry in Australia forward. Relevant stakeholders may be able to make more informed decision to design, install, operate and create policies regarding GSHP systems by using the learnings summarised in this thesis.

8.2 Recommendations for future work

In the process of conducting this research, the author noted some limitations, as well as recommendations for related works in the future.

8.2.1 Further collection of full-scale GSHP performance data in Australia

The full-scale field monitoring project conducted in Chapter 3 and 4 has helped to address the lack of GSHP systems performance data in Australia. However, field studies are often complicated and there can be many influencing factors which can affect the quality of the datasets obtained. Examples of some of these factors that were encountered in this research are the robustness of the instrumentation used, unexpected interference from a third party and duration of the monitoring project. The data analysis in this project was further complicated by the variation in the GHEs and GSHPs installed, as well as the user behaviour by occupiers of the properties monitored.

Based on the learnings from this project, the author recommends the following for a similar large scale GSHP systems monitoring project:

- More controlled experiments, such as by standardising building locations, building types, area to be air-conditioned, building's insulation used, type of GHEs, GSHPs and HVACs installed. A housing development such as a greenfield project may be suitable where there will be minimum variability from one house to another. This will allow performance comparisons between the systems.
- Data on the energy consumption pattern as well as the demographics of the occupiers should be gathered prior to the installation of the systems. One example is to collect past

energy bills for a retrofit project. This data is expected to capture user behaviour that may be used to improve the expected energy requirement prior to GSHP system design process.

- Detailed energy model for the building is recommended prior to the design stage to ensure the right GSHP capacity is chosen and installed. This is to minimise intermittent use of the system, which can compromise on the system's efficiency.
- Careful planning for the instrumentation installed, as well as using high-quality sensors. Any underground components should be protected from potential moisture ingress. Auxiliary systems that may be used for additional heating and cooling should be monitored for a complete capture of the actual total heating and cooling use.
- Training for the occupiers of how to use the systems and set points on thermostats. Literature has revealed that more knowledgeable occupiers tend to have better systems' performance. Furthermore, future surveys/interviews should be conducted to check whether the observed data reflects the occupants' actual usage of the systems.
- A longer monitoring period is recommended to observe potential interference between GHEs and the ground temperature changes over time. Interference between GHEs was not observed yet in this project, especially since most of the systems were underutilised.
- Finally, it is recommended to conduct a study with one or two houses installed with conventional systems. A side by side comparison between GSHP and conventional systems performance is still lacking, especially under a controlled condition. These data can further provide more information on the benefits of GSHP systems

A further field monitoring project is recommended to collect more performance and costs data. This will also help to establish local design manual, upskills local designers and installers, and also provide more information for policy creation. One policy example which may help to push the GSHP system industry is for the Government to provide some form of financial incentives or tax break to improve the financial viability of the systems. Various rebate currently exists for other renewable technology such as solar, wind and hydro in Australia, but none is available for GSHP systems usage.

8.2.2 Optimisation and field study of HGSHP systems

The hybrid GSHP (HGSHP) systems analytical study conducted in Chapter 5 and 6 revealed possible financial and environmental benefits compared to conventional or GSHP systems. Chapter 6 discusses a possible tradeoff for HGSHP systems when they are sized to either minimise the lifetime costs or emissions. Homeowners typically prefer to minimise their lifetime costs. Meanwhile, society or government may prefer to minimise the lifetime emissions generated from heating and cooling usage. These two optimised points are more likely represented as a different proportion of a GSHP and a conventional system mix as part of the HGSHP system.

The government can influence homeowners through financial incentives for them to install HGSHP systems at a different optimised point than the original one with the lowest lifetime costs.

Depending on the value of incentives given, it may be possible that this new optimised point will have lower lifetime costs and emissions compared to the original. This should pose as an attractive proposition for homeowners as they get to reduce their lifetime costs, but this can also benefit society as a whole with lower lifetime emissions, albeit with some additional financial costs to the government. The pricing of this incentive is not part of the scope of this thesis, but the author recommends an economist or a policymaker to work together with a GSHP system designer to explore this pricing strategy.

Additional field study is recommended to test the assumption of hybrid GSHP systems. The main assumption used in HGSHP system is to design the GSHP system to provide the baseload thermal demand and the system is supported by a conventional system during the hotter and colder part of the year. One potential flaw of this assumption is that the homeowners may not switch on the additional conventional system during this hotter and colder part of the year. In this scenario, the GSHP system is often used to provide more thermal energy than what it is designed for, which may lower the system's efficiency. Furthermore, overusing the GSHP system may change the ground temperature too much compared to the undisturbed ground temperature. This will exacerbate the problem and further deteriorate the system's efficiency. For this reason, conducting a field trial will allow designers to observe how the system is used and to see if this assumption is upheld, along with monitoring the performance under real-life usage scenario rather than the assumed pattern during the design of the system.

8.2.3 Optimisation and field study of DGSHP systems

In chapter 7, the benefit of a district GSHP (DGSHP) system is investigated and compared to a GSHP system. At present, an idealised 10 kW thermal load for various buildings were assumed. In a real district, this will not be the case. Hence, it is recommended to explore this area further in future studies. A full energy model should be developed for a real district development (such as the Fishermans Bends precinct), to encompass real heating and cooling demand for buildings with different thermal load peak demand and usage patterns. Furthermore, for the GHE components of the systems, the spatial space availability should be considered, as well as the potential thermal interference between the GHEs.

Finally, a field study of DGSHP systems is recommended to provide performance data for future adoption of the system. Studies related to real use of DGSHP systems are crucial since the world is moving into a 'distributed energy network', where energy is provided in decentralised locations for local usage. DGSHP systems fit into this idea well, where they can be used to share thermal energy between buildings and store them for later heating and cooling use. Possible studies to be conducted include the optimum GHEs configuration, how to minimise heat losses in the common loops, how to store, and transfer the available thermal energy efficiently. This technology can be integrated with other renewable technology, such as with solar thermal, solar PV and battery technology. Together, they can further improve the efficiency, financial and environmental benefits of the DGSHP systems.

9 References

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Appendix A

**Conference and journal papers published from the work
described in this thesis**

List of papers

1. **Aditya, G. R.**, Mikhaylova, O., Narsilio, G. A., & Johnston, I. W. (2018). Financial assessment of ground source heat pump systems against other selected heating and cooling systems for Australian conditions. IGSHPA research track Stockholm, Sweden., 2019.
2. **Aditya, G. R.**, Narsilio, G. A., Johnston, I. W., & Disfani, M. M. (2018, September). Full-Scale Instrumented Residential Ground Source Heat Pump Systems in Melbourne, Australia. In *International Symposium on Energy Geotechnics* (pp. 185-191). Springer, Cham
3. **Aditya, G. R.**, Narsilio, G. A., (2020). Environmental assessment of hybrid ground source heat pump systems. *Geothermics* **87**: 101868.



Financial Assessment of Ground Source Heat Pump Systems against Other Selected Heating and Cooling Systems for Australian Conditions

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ABSTRACT

Ground source heat pump (GSHP) systems can provide cost-effective space heating and cooling for buildings while using less fossil fuel compared to many conventional systems. Despite these benefits, they typically have higher upfront costs and longer payback periods than other heating and cooling systems. These costs are often seen as potential roadblocks for property owners to install GSHP systems over conventional systems. The financial attractiveness of GSHP systems can be increased by adopting a hybrid ground source heat pump (HGSHP) system where GSHP systems provide the baseload thermal energy with the balance provided by conventional systems. This paper assesses the lifetime costs of GSHP and HGSHP systems designed for seven major cities in Australia and compares these costs with the lifetime costs of conventional systems. The results indicate that adopting HGSHP systems in Australian climatic conditions (from tropical to cool temperate) and under current Australian installation and fuel costs can lower the normalised lifetime costs of heating and cooling compared to adopting a GSHP or a conventional system only for the same applications.

INTRODUCTION

In Australia, electricity is used for space heating and cooling of many buildings. The Australian Bureau of Statistics (2014) reported that for residential heating, 38% of residents use electricity and 30% use gas, while for cooling 49% residents use an electrical air conditioner. Most of the electricity in the country is generated from coal and gas, which are traditionally low cost and reliable energy sources. However, burning these fuels to generate electricity leads to high greenhouse gas (GHG) emissions. Gas is also used directly in furnaces for heating which also contributes significantly to the overall GHG emissions.

To achieve long-term environmental sustainability, electricity and gas consumption needs to be reduced. Ground Source Heat Pump (GSHP) technology can contribute to this reduction because GSHP systems typically have higher coefficients of performance (CoP) compared to conventional heating and cooling systems. For example, GSHP systems have been reported to have a CoP between 3 to 5 (Bloom and Tinjum, 2016; Liu and Spitler, 2014; Lu et al., 2017; Michopoulos et al., 2007; Trillat-Berdal et al., 2006). Conventional heating and cooling systems, such as a reverse cycle air conditioners (RCAC, Air Source Heat Pump Systems), typically have a CoP of 2 to 4 (Huang, 2015; Liu and Spitler, 2014; Lu et al., 2017; Self et al., 2013; Wu, 2009). Other conventional systems which use electricity and gas to provide heating operate at a CoP of less than 1 and unable to provide cooling. Hence, GSHP systems are

typically deemed to provide cost-effective heating and cooling to buildings while using less fossil fuels than most conventional systems.

Despite their efficiencies, property owners find it difficult to adopt GSHP systems due to their higher upfront costs and longer payback periods (Karytsas and Chorapanitis, 2017; Lu et al., 2017). One strategy to reduce these costs and payback periods is to utilise hybrid ground source heat pump (HGSHP) systems, whereby GSHPs provide the baseload thermal energy to buildings with the balance provided by other, usually conventional, systems during particularly hot and cold periods of the year. These systems take advantage of the relatively low installation costs of conventional systems and the relatively low operating costs of GSHP systems to make HGSHP systems attractive financially (Alavy et al., 2013; Mikhaylova et al., 2016; Nguyen et al., 2014). Several recent studies investigated the optimum sizing strategy for HGSHP systems by adjusting the *shave factor* of the systems. The shave factor is defined as the proportion of the total heating or cooling peak load provided by the GSHP (Alavy et al., 2013; Mikhaylova et al., 2016; Nguyen et al., 2014). The most optimum configurations of hybrid systems are the ones that result in the lowest net present values over the lifetime of the systems.

This study assesses the lifetime costs of GSHP and HGSHP systems for seven major cities in Australia (see Table 1) and compare them with lifetime costs of conventional systems. Each of these Australian cities has significantly different climatic conditions, and hence, energy needs. To compare HGSHP systems with other heating and cooling options, the hybrids are optimised using extensions of previously published optimisation methods discussed in Alavy et al. (2013) and Mikhaylova et al. (2016).

DATA AND METHODOLOGY

Climatic conditions and thermal loads

This study covers a wide range of climatic conditions, which vary from a tropical climate in the north to a cool temperate climate in the south. The hourly outside air temperature (OAT) data based on the typical meteorological year is retrieved for all the chosen cities from Meteonorm (2017). These hourly OATs are used to estimate the undisturbed ground temperature (T_g) at shallow depths in each city. T_g is assumed as the average annual OAT plus 2°C as described in IGSHPA (2009). The heating and cooling loads in each city were calculated based on the bin method by IGSHPA (2009) with a balance point of 17.5°C . This study assumes all buildings are residential with a peak load of 10 kW. For simplicity, the effect of humidity in cooling operations is disregarded in this paper. Table 1 presents an overview of the input parameters and the peak heating and cooling load for each city.

Table 1. Locations, design temperatures and peak heating and cooling loads

	Lat (deg)	Long (deg)	t_{dh} ($^\circ\text{C}$)	t_{dc} ($^\circ\text{C}$)	T_g ($^\circ\text{C}$)	Q_h / Q_c (kW)
Adelaide	34.9 °S	138.6 °E	5.9	33.9	18.7	7.1 / 10.0
Brisbane	27.5 °S	153.0 °E	7.3	30.0	22.2	8.2 / 10.0
Cairns	16.9 °S	145.8 °E	14.9	32.0	26.5	1.8 / 10.0
Hobart	42.9 °S	147.3 °E	3.4	25.2	12.9	10.0 / 5.5
Melbourne	37.8 °S	145.0 °E	5.6	31.9	16.5	8.3 / 10.0
Perth	32.0 °S	115.9 °E	5.6	34.2	19.9	7.1 / 10.0
Sydney	33.9 °S	151.2 °E	7.9	28.6	20.1	8.6 / 10.0



Notation: t_{dh} = heating design temperature, t_{dc} = cooling design temperature, T_g = estimated ground temperature at shallow depth. Q_h or Q_c = estimated peak heating / cooling loads

Heating and cooling options

The most common heating and cooling systems used in Australia are considered herein as conventional alternatives for GSHP systems. As such, the following options with their assumed CoPs are compared:

- (1) Heating and cooling by an RCAC (CoP 2.5);
- (2) Heating with a gas furnace (CoP 0.9) and cooling by an RCAC (CoP 2.5);
- (3) Heating and cooling by GSHP (CoP 4);
- (4) Heating and cooling by HGSHP system (HGSHP1) with a GSHP (CoP 4) and an RCAC (CoP 2.5); and
- (5) Heating and cooling by HGSHP system (HGSHP2) with a GSHP (CoP 4), a gas furnace (CoP 0.9) for heating and an RCAC (CoP 2.5) for cooling.

This study considers only vertical ground heat exchangers (GHEs), where the required GHE length for the GSHP and HGSHP systems are calculated using the ASHRAE design approach shown in Equation 1 (Philippe et al., 2010).

$$L_{GHE} = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_c R_{6h}}{T_m - (T_g + T_p)} \quad (1)$$

Table 2 summarises most design parameters employed, including those used in Equation 1. To simplify the comparison between different locations, the same ground conditions (but not T_g) and GHE geometry are assumed in all sites.

Financial Assessment

Installation costs, inflation rates and discount rates for electricity and gas, and life spans of the systems are kept constant for all locations for simplicity. These parameters are based on the work by Lu et al. (2017) and are shown in Table 3. In particular, it has been assumed that the life spans of GSHP systems are 20 years. The life spans of both RCAC and gas boilers are assumed to be 10 years each. This means that both systems will need to be replaced once over the 20 years design life. It is assumed that the replacement costs of the RCAC and gas boilers are the same as their original prices because the yearly price increase of the equipment is aligned with the discount rate. Since a 10 kW system is relatively small, maintenance cost is not included in the analysis. All the financial analysis are conducted in Australian dollars (A\$), which at present is around US\$ 0.79.

The operating cost for the heating and cooling systems are calculated based on the current retail prices of electricity and gas in the cities studied. These prices are taken from the major energy retailers (Aurora Energy, 2017; Origin Energy, 2017; Synergy, 2017) and shown in Table 4 below. Whenever possible, the prices have been calculated based on the weighted price average during peak, off-peak and shoulder periods. It is important to note that the operating cost of the circulation pumps is assumed negligible for these small residential buildings.

Based on the above inputs, the Net Present Costs (NPC) were calculated for each of the heating and cooling option in the seven cities considered using Equation 2.

$$NPC = \sum \frac{C_t}{(1+r)^t} \quad (2)$$

where C_t represents the cash outflow at time t which can be a capital cost or an operating cost. This cost at time t will be discounted back at interest rate r over the 20 year design life of the system. The NPC calculated here represents the present value of all outgoing cash flows during installation, operation, replacement (if necessary) over 20 years.

Table 2. Parameters used for sizing of GHEs

Design parameter (units)	Description	Value
q_h, q_m, q_y (kW)	Peak hourly, monthly average and yearly average ground loads	Calculated based on building thermal demand, heating and cooling shave factors, and COP of GSHP
R_b (mK/W)	Effective thermal resistance of the borehole, calculated based on the multipole method (Hellström, 1991)	0.103
λ (W/mK)	Thermal conductivity of ground. It is used to calculate R_{6h} , R_{1m} , and R_{10y} below based on the cylindrical heat source solution proposed by Carslaw and Jaeger (1959)	2.5
R_{6h} (mK/W)	Effective thermal resistance of the ground to 6 hours of ground load	0.106
R_{1m} (mK/W)	Effective thermal resistance of the ground to 1 month of ground load	0.146
R_{10y} (mK/W)	Effective thermal resistance of the ground to 10 years of ground load	0.153
T_g (°C)	Undisturbed ground temperature at shallow depths	Listed in Table 1
$T_{m,c}$ (°C)	Mean GHE fluid temperature in cooling operation	32.2 (= 90 °F, chosen value)
$T_{m,h}$ (°C)	Mean GHE fluid temperature in heating operation	4 (= 40 °F, chosen value)
T_p (°C)	Temperature penalty	0 (GHE is thermally independent)

Table 3: Parameters used for financial assessment

Parameter (units)	Value	Note
Cost of drilling (A\$/m)	80	Borehole installation
Cost of GSHP (A\$/kW)	2,000	Equipment and installation of the system
Cost of RCAC (A\$/kW)	1,000	Equipment and installation of the system
Cost of gas boiler (A\$/kW)	500	Equipment and installation of the system
Electricity inflation rate (%)	6.2	
Gas inflation rate (%)	6.14	
Discount rate, r (%)	3.5	
Life span of GSHP system (years)	20	
Life span of RCAC and boiler (years)	10	
Replacement of RCAC and gas furnace	Every 10 years	
Design life (years)	20	

Table 4: Electricity and gas price considered

Cities	Electricity price (c/kWh)	Gas price (c/kWh)
Adelaide	31.3	13.0
Brisbane	22.0	10.6
Cairns	22.0	10.6
Hobart	20.2	12.6
Melbourne	27.6	9.4
Perth	27.2	10.3
Sydney	23.8	12.6

RESULTS AND DISCUSSIONS

Annual thermal demands

The calculated annual thermal demands for a 10 kW system run continuously in all the cities are shown in Figure 1. As expected, the annual thermal demand is highly correlated with the climatic conditions in each city presented in Table 1. For example, the results indicate that Hobart and Melbourne are heating dominant while the rest of the cities are cooling dominant. Perth is the city which has the most balanced heating and cooling thermal demands amongst all the cities considered. Since the demand for heating in Cairns is minor, less than 0.2 MWh, this study assumes that heating is not required in this city.

Net operating costs of GSHP and conventional systems

The computed NPCs for GSHP and conventional systems are shown in Figure 2. The NPCs are broken down into the components associated with mechanical plant costs, GHE installation costs, and operating costs. Since heating is not needed in Cairns, only one conventional system (RCAC) is considered in this city.

The capital cost component of GSHP systems (plant and GHE costs) are always higher than conventional systems due to the GHE cost components of the system. The GHE length in each city is determined by the unique thermal load pattern as well as the undisturbed ground temperature. The calculated GHE length varies from 200 m in Melbourne to 600 m in Cairns as shown in Figure 2 below. In Cairns, additional GHE length is required to allow heat dispersion to the ground without compromising a GSHP system’s efficiency in this highly cooling dominant climate.

Figure 2 also shows that the operating costs of GSHP systems are always lower compared to conventional systems in the same location. From the same figure, operating cost components represent the largest shares of the NPCs of most systems in all locations even after accounting for the high GHE installation costs.

In all locations except in Cairns, the GSHP systems are the cheapest heating and cooling options compared to the conventional systems. The distinct results for Cairns are due to the high GHE lengths needed as discussed above. This means that the financial benefits generated from the lower operating cost from using GSHP systems over 20 years design life are not enough to offset the high GHE installation cost in this city.

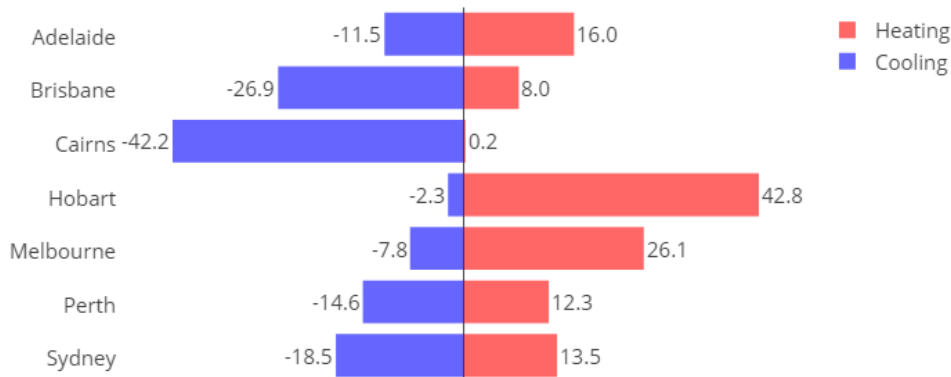


Figure 1 Annual heating and cooling demands in MWh of a typical 10 kW system. Negative values indicate cooling

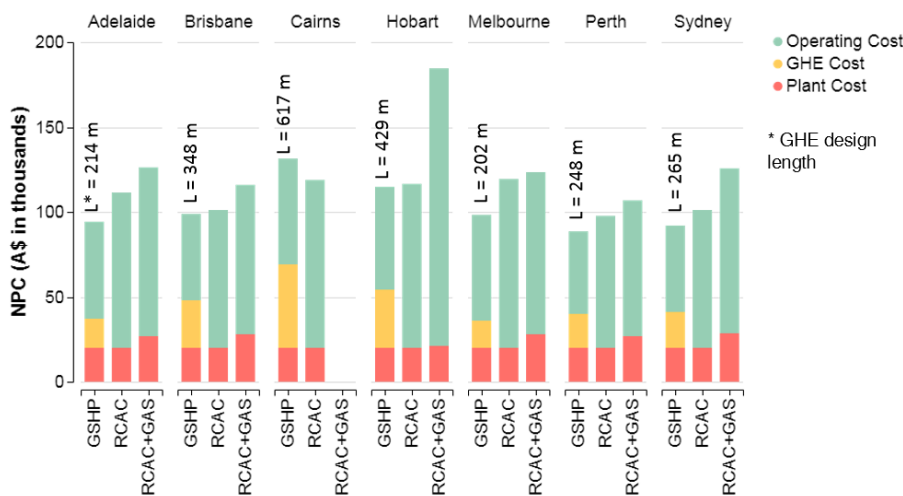


Figure 2 NPC in A\$ for GSHP and conventional systems

Hybrid ground source heat pump systems

The previous section has demonstrated that GSHP systems generally have lower NPCs compared to conventional systems. However, their high upfront capital costs can make GSHP systems a less desirable heating and cooling option in Australia. The financial attractiveness of GSHP systems can be increased by adopting hybrid ground source heat pump (HGSHP) systems. In such systems, GSHPs provide the baseload thermal energy to buildings which are topped up by conventional systems during the hotter and colder days of the year. An example of this is shown in Figure 3 below where if a GSHP system in Sydney is sized to provide 50% of peak heating and cooling load (a 50% shave factor giving 4.3 kW and 5.0 kW peak load), the GSHP systems can meet around 83% of the annual thermal energy requirements. Note that contrary to the northern hemisphere, winter in Australia occurs in mid-year.

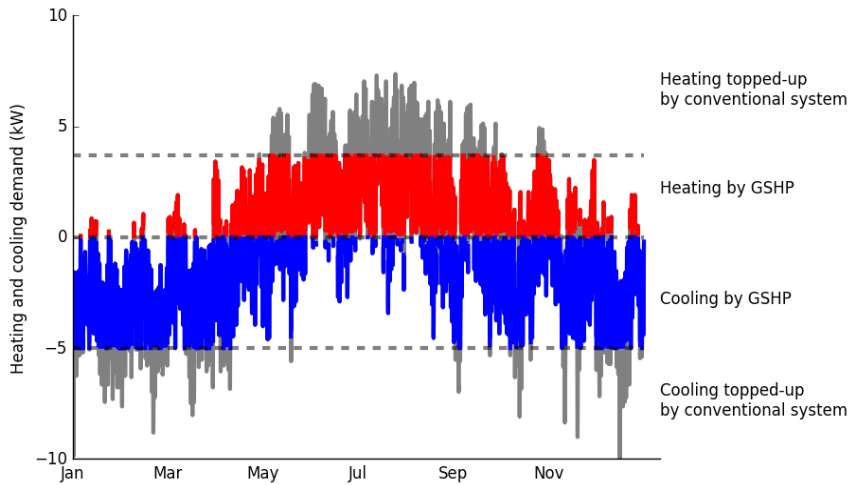


Figure 3 An example of a HGSHP in Sydney sized to meet 50% of peak heating and cooling power demands

This section explores financial benefits of HGSHP systems that are sized to achieve minimum NPC of these systems over 20 years life span. The optimisation of the HGSHP systems performed using the method described in Mikhaylova et al. (2016). The NPC is further normalised by the total amount of thermal energy provided to the buildings over 20 years to allow comparisons between the cities, which is expressed as the Total Normalised Cost (TNC) in A\$/MWh.

$$TNC = \frac{NPC}{\text{Total thermal energy provided by the system}} \quad (3)$$

Two HGSHP systems are considered here, where HGSHP1 is a combination of GSHP and RCAC systems, while HGSHP2 is a combination of GSHP, RCAC, and gas furnace systems. For each HGSHP system, the TNC is calculated for heating and cooling shave factors from 0% to 100% with a step size of 2%. In these calculations, it is assumed that all input parameters are the same as stated in Table 2 to Table 4 and no additional costs arising from the complexity of installing hybrid systems over conventional systems since these costs could be minor for residential installations. This assumption may need to be revised for larger, more complex control of commercial systems.

As an example, Figure 4 presents the TNCs for HGSHP1 and HGSHP2 in Sydney. The bottom left corner of the plots represents 0% shave factor or, effectively, a conventional system. The top right corner of the plots represents a 100% shave factor or, effectively, a GSHP system. The points in between represent the calculated TNC

for different shave factor combinations of the HGSHP systems, where the TNCs are represented by contour lines. The lowest TNC is identified in the plot to indicate the most cost-effective shave factor combination for a HGSHP system where the system costs the least for a given amount of thermal energy produced. As discussed earlier, Sydney has a relatively balanced climate with a similar amount of heating and cooling energy required for a typical residential building. For this reason, both shave factors considerably influence the TNCs.

From Figure 4, the lowest TNC for HGSHP1 in Sydney is A\$136/MWh where the GSHP system is designed to provide 62% and 54% of the peak heating and cooling power demands respectively (Figure 4a). This enables the GSHP system to meet around 88% of the thermal demand. For the same city, the lowest TNC for HGSHP2 is A\$140/MWh, where the GSHP system is designed to provide 90% and 78% of the peak heating and cooling power demands respectively (Figure 4b). This enables the GSHP system to meet around 98% of the thermal demand. The plots in Figure 4 demonstrates that it is important to optimise HGSHP system sizing to maximise return on investment.

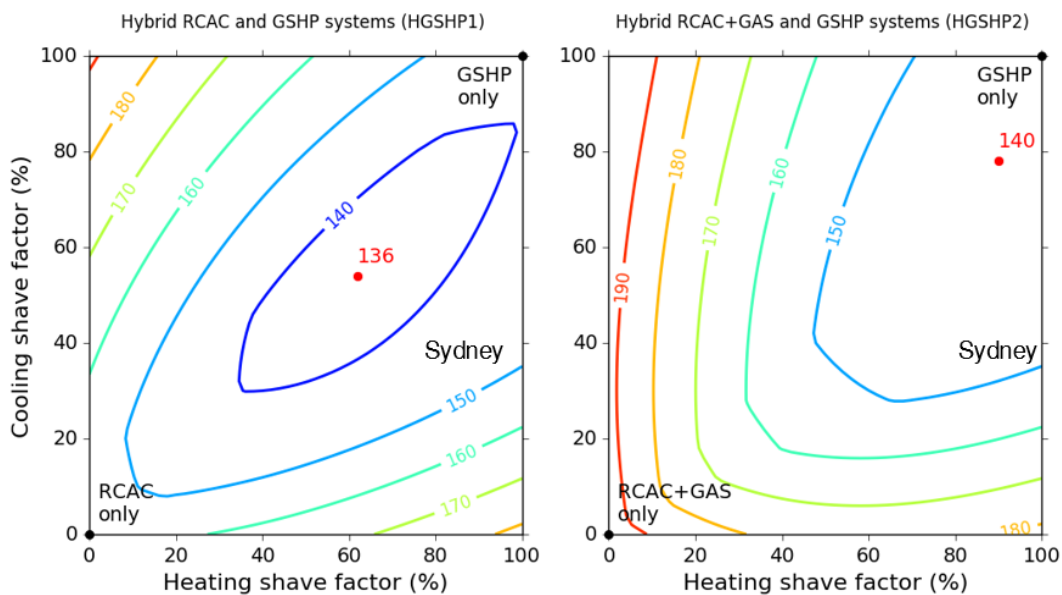


Figure 4 TNC values in A\$/MWh of HGSHP1 (a) and HGSHP2 (b) systems for Sydney.

Figure 5 summarises the TNC calculations for all five heating and cooling options in the seven cities considered. For HGSHP systems, the TNCs values of optimised configurations (the lowest TNC) are shown. The figure also presents the TNC values normalised with respect to the TNC of GSHP systems in each city, shown as values above each column. A normalised TNC of 1 represents the TNC for GSHP systems in each city. If a normalised value of TNC is more than 1, the system's TNC is higher than the TNC of a GSHP system in the same city and vice versa.

The TNC for GSHP systems varies from A\$127/MWh in Hobart to A\$171/MWh in Adelaide. This suggests that 1 MWh of thermal energy supplied by a GSHP system over 20 years is the cheapest in Hobart and the most expensive in Adelaide. These results directly correlate with the unit costs of electricity in these cities (Table 4). Overall, the TNCs of GSHP systems are lower compared to conventional systems, in all cases except in Cairns.

For all locations, the TNC for both types of HGSHP systems are 1 to 10% lower than the TNCs of GSHP systems, which means that the hybrid systems are more financially beneficial than GSHP systems. However, the benefits may be relatively minor. Another observation is that the capital costs of hybrid systems are lower than the capital costs of GSHP systems, which is mainly due to the reduction in the required GHE length. This means that

hybrid systems can be more attractive than GSHP systems due to lower required initial investments which can be the primary motivation to install HGSHP systems over GSHP systems for some home owners.

In comparison to conventional systems, HGSHP systems can reduce TNC by up to 40% as shown by the HGSHP2 system in Hobart. It is important to note that unlike the GSHP system, a HGSHP system in Cairns has a lower TNC than a conventional system, where the TNC for HGSHP1 in Cairns is A\$138/MWh compared to A\$140/MWh for a conventional system. In this case, the hybrid system needs to be sized to meet 24% of the cooling peak load, assuming that the system does not require any heating in Cairns.

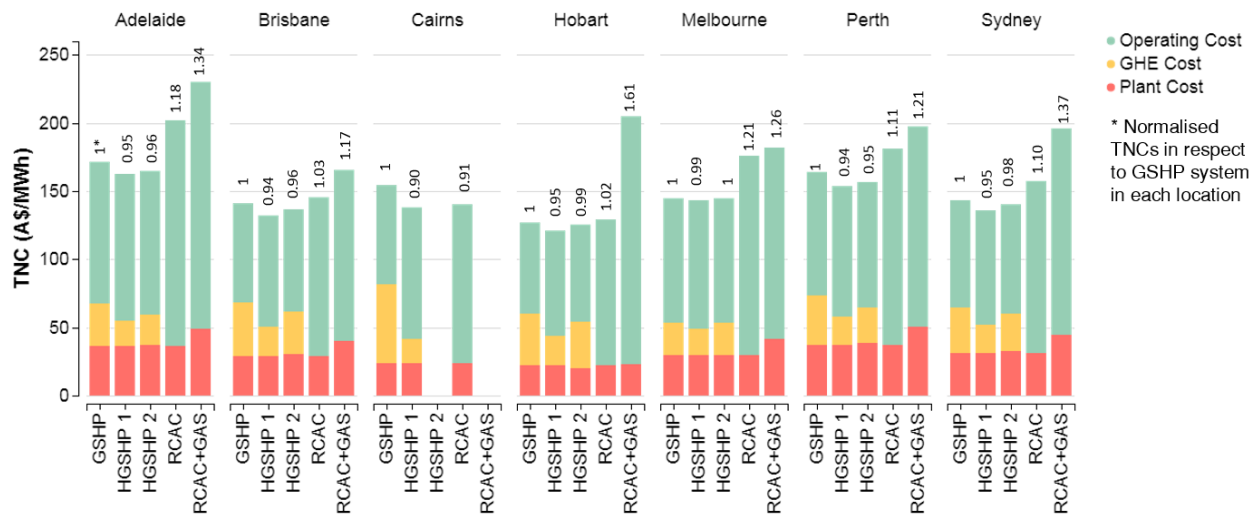


Figure 5 Lowest TNC in A\$/MWh comparisons between HGSHP1, HGSHP2, GSHP and conventional systems

CONCLUSION

This paper has shown that ground source heat pump (GSHP) systems can have lower net present costs compared to conventional systems even with the high installation costs of the systems in Australia. Although for the specific cases considered, hybrid systems were only marginally cheaper than GSHP systems, they appear to have the potential to further reduce lifetime costs, particularly in cooling dominated climates. However, further detailed and/or sensitivity analyses are necessary. In a hybrid ground source heat pump (HGSHP) model, the GSHP systems provide the baseload thermal energy to buildings, which is topped up by conventional systems during the hotter and colder days of the year.

HGSHP systems can be more attractive than GSHP systems due to lower required initial investments. However, HGSHP systems need to be sized to maximise the financial investment return. This can be a complicated process where designers need to consider the climatic conditions, as well as the energy prices in the locations where the system is being installed. Adopting a HGSHP system in Australia can reduce the total normalised cost over 20 years life span of the systems by up to 10% and 62% compared to an equivalent sized GSHP and conventional systems respectively depending on location. With the wide range of climatic conditions considered, the new insights developed may be transferable to other parts of the world with similar climatic conditions.

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Full-scale instrumented residential ground source heat pump systems in Melbourne, Australia

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Abstract: Ground-source heat pump (GSHP) systems typically show higher efficiencies than conventional systems for space heating and cooling of buildings. However, the availability of GSHP systems performance data is still limited, especially in Australia due to the small number of GSHP systems installed and monitored. This paper provides some initial results from a GSHP systems monitoring project conducted on ten residential properties in the greater Melbourne region of Australia. The data measured reveals an estimated Coefficient of Performance between 2 and 4.9. The reasons for these variations in measured system efficiency with respect to design expectations are discussed.

Introduction

Ground source heat pump (GSHP) or shallow geothermal systems can efficiently heat and cool buildings using sustainable geothermal energy accessed via ground heat exchangers (GHEs). In closed-loop systems, GHEs comprise pipes embedded in specifically drilled boreholes or trenches or even built into foundations. In Australia, most of the electricity is generated from fossil fuels. Given that GSHP systems generally operate at a coefficient of performance (CoP) of between 3 and 5, the substitution of commonly used electrical heating and cooling systems with GSHP systems could potentially significantly reduce energy consumption and greenhouse gas emissions.

Even though there have been experimental studies of GSHP systems published worldwide, the availability of high-quality datasets on performance and usage patterns are still rare, especially under real life thermal loads.

In Australia, the availability of these datasets are further limited due to the small number of GSHP systems installed, and fewer still that have their performance monitored in detail. To date, the only available performance data in Australia corresponds to a few commercial buildings, a school, a house and an aquatic centre (Geoscience Australia, 2007; Huang, 2015; Kivi, 2014; Mikhaylova et al., 2015;

Payne et al., 2015). To redress this, The University of Melbourne has been undertaking a full-scale pilot direct geothermal energy demonstration project, whereby the performance data from a number of properties in greater Melbourne have been collected for several years. This paper provides some initial experimental results from ten residential properties.

Full-scale experimental studies

Melbourne has a temperate climate, and based on the typical meteorological year (TMY) gathered from Meteonorm (2017), typical design outside air temperatures vary between 1 and 37°C. A residential GSHP system is typically designed for continuous operation based on the bin method (IGSHPA, 2009), where no heating or cooling is needed when the outside air temperature is between 15.5 and 19.4°C (60 and 67°F). Outside this range, and accounting for 82% of the year, heating or cooling would be needed for Melbourne (see Fig. 1).

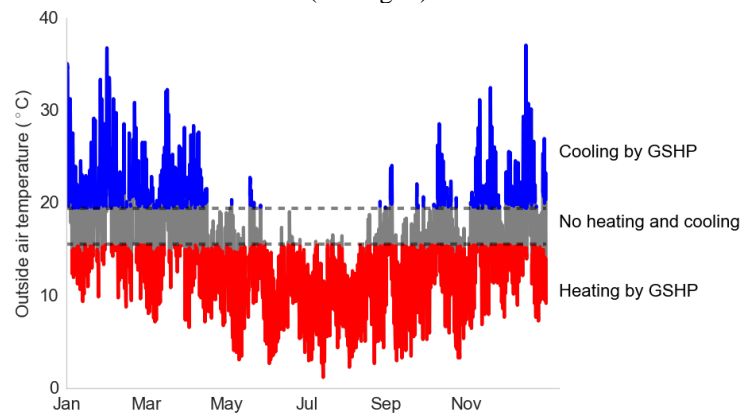


Fig. 1: Typical Melbourne design temperatures for GSHP systems

The locations of the residential properties monitored are shown in Fig. 2. This range of properties was expected to be able to give an indication of typical variations in performance of such properties for a range of house sizes, patterns of use, local weather conditions and variations in geology commonly encountered in Melbourne. The conditioned floor area, along with whether the building is retrofitted or newly built, the geology, the number, orientation and total length of GHEs, the capacity of the GSHPs and details of the distribution systems installed in these properties, are summarized in Table 1.

Table 1: Summary of site conditions and GSHP installations at the monitored properties

Property location (refer to Fig. 2)	Conditioned floor area (m ²)	Retrofitted (R) or newly built (NB)	Geology ¹	Number, orientation ² and total GHE length (m)	GSHP ^{3,4,5} heating/cooling capacity (kW)	Distribution systems
Ashburton	300	NB	Siltstone & minor sandstone	4, V, 360	³ 32/28	Floor hydronic heating, FCU ⁶ for cooling, water & pool heating
Buninyong	150	R	Deep marine deposits & sandstone	4, H, 160	^{3,5} 8/8	FCU for heating and cooling
Cheltenham	100	R	Sands with minor clay	2, V, 110	⁴ 6/9	Ducted heating and cooling
East Brunswick	50	R	Basalt	2, V, 130	^{3,5} 8/8	FCU for heating and cooling
East Melbourne	60	NB	Basalt	2, V, 120	³ 11/9	Ducted heating and cooling, water & spa heating
Footscray	100	R	Basalt	2, V, 110	⁴ 8/10	Ducted heating and cooling
Inverloch	200	NB	Siltstone & sandstone	6, V, 300	³ 18/17	Floor hydronic heating and cooling & hot water
Kangaroo Ground	400	NB	Siltstone	9, S, 320	³ 16/15	Floor hydronic heating and FCU for cooling
Main Ridge	280	NB	Basalt	8, S, 320	³ 22/17	Floor hydronic heating and hot water
Thornbury	50	R	Siltstone & minor sandstone	2, V, 100	^{3,5} 6/6	FCU for heating and cooling

¹ Based on the Geological Map of Melbourne from Energy and Earth Resources (1959)² V = vertical GHEs, H = horizontal GHEs (straight pipe), S = horizontal GHEs (slinky)³ Water to water GSHP⁴ Water to air GSHP⁵ Experimental GSHP manufactured locally⁶ Fan coil unit



Fig. 2: Location of the ten monitored properties

To measure GSHP system performance, sensors were installed in each of the systems installed at the properties. Fig. 3 presents a typical instrumentation schematic for a property with vertical GHEs installed. The instrumentation consists of thermistors to measure the ground temperature along the ground loop, thermistors and flow meters to measure the temperatures and flow rate of the water flowing in and out of the GSHP on the ground side (and the building side when applicable in water to water systems), and a power meter to measure the electrical power consumption of the GSHPs, circulation pumps and fans required to run the system. All the monitoring data at each property is collected through a data logger, which can be accessed remotely for data transmission through the internet. Most of data collection in this project started in 2015.

Results and discussion

A summary of the performance data for all monitored properties is shown in Table 2. It can be observed that all properties were heating dominant. This is confirmed by Fig. 4 which shows a typical energy demand pattern for a period of more than two years for one of the properties (Cheltenham).

Further, most of the properties have run fractions of only about 10 to 20%. This is in contrast to the expected usage of around 82% based on the bin method applied continuously. The temperate climate in Melbourne is mild enough to result in minimal heating and cooling demand throughout the year. In particular, during the shoulder periods around April and October, very little heating or cooling is required. This is in contrast to many other parts of the world where either heating or cooling is typically needed throughout the whole year.

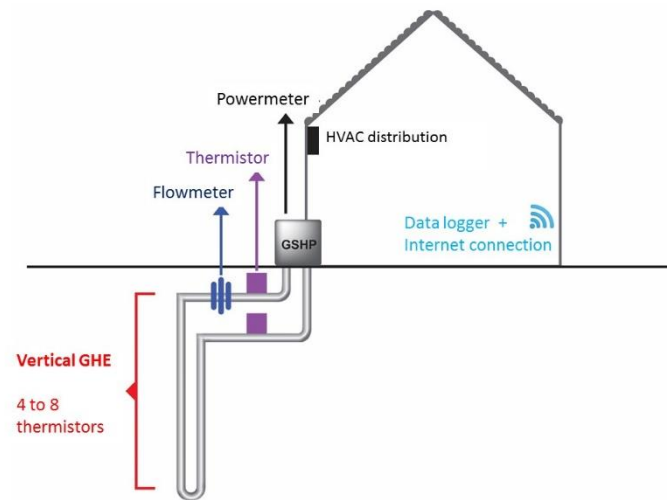


Fig. 3: Typical instrumentation for a property with a vertical GHE installed

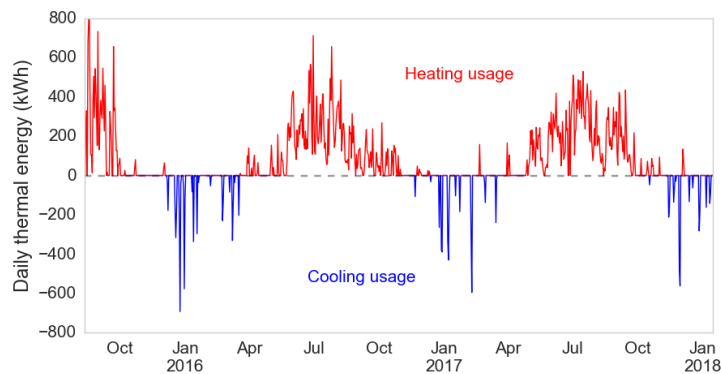


Fig. 4: Daily thermal energy demand for the Cheltenham property

It must be noted that, the bin method estimates a building's thermal demand based on the ambient air temperature and it does not account for user behavior which may be possible in a temperate climate. These conditions usually allow systems to be turned off during the day if occupants are out at work. In such a climate, it may also be possible to turn the systems off during the night. It follows that for such a climate, the actual usage observed can be significantly lower than the expected designed usage using the bin method.

Table 2: Summary of GSHP system performance at the monitored properties

Properties location (refer to Fig. 2)	Monitored period	Total usage (hours)		Run time fraction (%) ⁸	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF ⁹	CoP ¹⁰
		Heating	Cooling		Heating	Cooling			
Ashburton	² Jun '15 – Jan '18	4,568	2,967	36	80,508	16,495	26,339	3.7	4.6
Buninyong ¹	Nov '16 – Jan '18	757	288	10	4,900	1,495	2,330	2.7	2.9
Cheltenham	Aug '15 – Jan '18	1,186	145	6	6,208	928	1,978	3.6	4.1
East Brunswick ¹	³ Aug '15 – Jan '18	177	-	-	538	-	294	1.8	2.3
East Melbourne	⁴ Jun '15 – Jan '18	2,232	1,512	17	12,414	4,593	6,216	2.7	3.3
Footscray	⁵ Jun '15 – Jan '18	2,147	407	12	12,022	1,861	5,687	2.4	2.7
Inverloch	Jan '16 – Jan '18	2,548	594	17	27,038	6,328	9,763	3.4	3.8
Kangaroo Ground	Sep '16 – Nov '17	720	302	10	5,590	3,033	1,905	4.5	4.9
Main Ridge	⁶ Sep '15 – Jan '18	1,013	-	5	16,747	-	4,736	3.5	4.0
Thornbury ¹	⁷ May '15 – Jan '18	1,245	858	9	2,925	960	2,412	1.6	2.0

¹ Properties with an experimental GSHP manufactured locally.. GSHPs at East Brunswick and Thornbury were the first iteration, which may explain lower SPF than at Buninyong

² Excluding February 2017 – July 2017 when the data logger malfunctioned

³ GSHP often malfunctions, thus indicating minimal usage hours. For this reason, run time fraction was not calculated as it is not representative

⁴ Excluding December 2017 when data logger was off

⁵ Excluding January 2017 – February 2017 when flow meter malfunctioned

⁶ Excluding July 2017 – September 2017 when data was not collected. This house is a holiday house and not the main place of residence, hence the low usage hours of the system. GSHP system was also designed for heating mode only

⁷ Excluding June 2015 to August 2015 when data logger was off

⁸ Run time fractions are adjusted to exclude periods when analysis could not be performed due to data collection problems (actual usage may be more than the stated run time fraction)

⁹ Seasonal performance factor (SPF) = total energy provided to the building / total electrical energy used. The power consumption including GSHP, circulation pumps and fans

¹⁰ Estimated CoP of the GSHP (without the circulation pumps and fans power consumption).

The GSHP systems monitored have seasonal performance factors (SPF) between 1.6 and 4.5. These SPFs reflect the efficiency of the systems as a whole because they include the power consumption of the GSHPs, circulation pumps and fans to run the systems, as measured in this project. The CoPs of the GSHPs were estimated on the basis of the rated power consumption of the other mechanical equipment and are also presented in Table 2. These CoPs are between 2 and 4.9.

The systems at East Brunswick and Thornbury have low CoPs because they were retrofitted with a locally manufactured experimental GSHP which turned out to perform less efficiently than expected. The system at Buninyong was driven by an updated but still experimental local GSHP which still produced a relative low CoP. Although not known at the design stage, the system at Footscray was significantly under designed and hence, returned a relatively low CoP.

If the results from these four locations were discounted, the CoPs recorded for the remaining six properties were between 3.3 and 4.9. This range seems to be similar to the range of CoPs for various GSHP systems reported in the literature including 3.4 in France (Trillat-Berdal et al., 2006), 3.3 at the ASHRAE headquarters in USA (Liu and Spitzler, 2014), 3.9 in Southern Germany (Luo et al., 2015), and 4.4 to 5.2 in Northern Greece (Michopoulos et al., 2007)

It may be worth noting that a close inspection of the monitored data showed that the GSHPs switched on and off more than would have been expected. This may have occurred because most of the GSHPs installed were single speed GSHPs without buffer tanks operating in relatively low demand systems. These conditions are likely to have had a negative impact on the observed CoPs, outweighing the potential ground thermal performance improvement resulting from a low run fraction.

The above discussion suggests that the bin method may not be the best design approach for residential GSHP systems in a temperate climate and another or modified design method may be required. Alternatively, hybrid GSHP systems may be a better option. This would require GSHP systems providing the base load thermal demand with conventional systems servicing the hotter and colder periods of the year.

Conclusions

This paper presents the preliminary results of the performance of GSHP systems installed in ten residential properties around Melbourne, Australia. The preliminary results indicate that these systems have CoPs that are comparable to other GSHP systems around the world.

However, what is clear is that the recorded run time fraction for all the properties was significantly lower than would have been expected through the use of the bin method. This is probably as a result of Melbourne having a temperate climate which allows heating and cooling systems to be turned off for significant parts of the day and the year. This suggests that a different design method may be more appropriate

for GSHP systems in such a temperate climate so that smaller geothermal systems can be used to give lower capital costs. Alternatively, this pattern of usage may be better served through the use of hybrid GSHP systems.

Acknowledgements

The authors acknowledge the financial support for this project by the Victorian Government's Department of Environment, Land, Water and Planning. They are also grateful to all the property owners/tenants who allowed monitoring of their systems along with associated installers.

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Errata for Switzerland conference paper

Prior to the conference presentation, the main author (myself) noticed an error in the graph presented (Fig 4). The error does not change the message of the analysis. At that time, it was already too late to change the graph prior to the printing of the conference proceeding. However, the correct graph was presented during the conference presentation and is provided here.

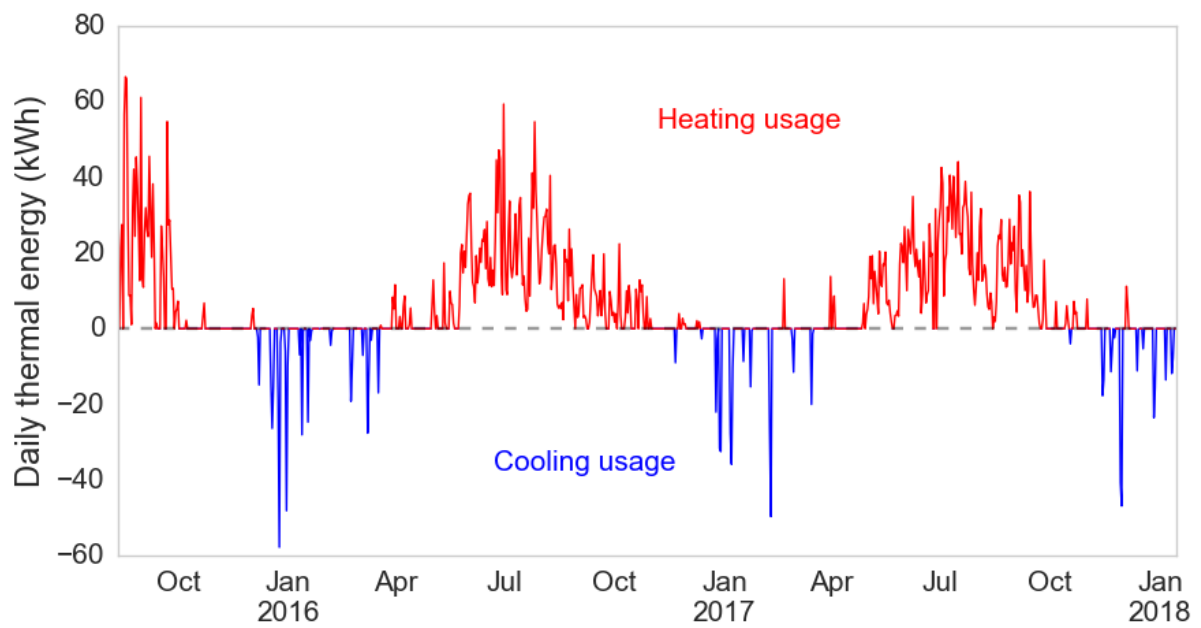
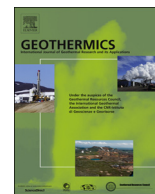


Figure 4: Daily thermal energy demand for Cheltenham property



Environmental assessment of hybrid ground source heat pump systems

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ABSTRACT

A hybrid ground source heat pump (HGSH) system can provide cost-effective heating and cooling for buildings. This system is normally designed to minimise lifetime costs. However, the lowest lifetime cost solution is typically not the one with the lowest emissions. With the recent increase in the awareness of climate change, society often desires to minimise the emissions generated from heating and cooling systems. In this paper, an HGSH system design method is proposed with the objective that considers both costs and emissions by using a Pareto optimal approach. The design of such system is affected by the climatic conditions, the efficiency of the heating and cooling systems, the energy price and emissions for electricity and gas at each location. Potential changes in these factors are also investigated in this paper.

1. Introduction

Worldwide energy use is expected to rise due to an increase in population and global warming. In Australia, electricity is the most dominant energy source used for space heating and cooling, where 38 % of households use electric heaters and 49 % use reverse cycle air conditioners (RCACs) for cooling (Australian Bureau of Statistics, 2014). The associated carbon emissions are exacerbated by the fact that 60 % of Australian electricity generated in 2018 was from coal (Department of Environment and Energy, 2019). Not surprisingly, it was reported that the electricity sector is the biggest polluter, representing 33 % of the carbon emissions in Australia (Climate Council Australia, 2018). A global analysis paper by Ang and Su (2016) reported that in 2013, Australia was the fifth most carbon-intensive electricity producer in the world, with an electricity emission factor of 0.7806 kgCO₂e/kWh of electricity used. In comparison, Ang and Su (2016) estimated a worldwide average of 0.52 kgCO₂e/kWh, which means that compared to the worldwide average, there is an additional 50 % carbon emissions for each kWh of electricity used in Australia.

This electricity consumption should be reduced to achieve long-term environmental sustainability and also to meet Australia's commitment at the Paris Climate Change Conference to reduce GHG emission by around 150 Mt CO₂e by 2030 (Department of Environment and Energy, 2015). Furthermore, it has been reported that emission abatement in the electricity sector is more cost-efficient compared to reducing emissions in other sectors (Climate Council Australia, 2018). One way to reduce this electricity consumption worldwide is by using more efficient heating and cooling systems, such as ground source heat

pump (GSHP) systems.

Research on GSHP systems has increased in recent years and details about the systems can be found elsewhere (Brandl, 2006; Johnston et al., 2011; Sanner et al., 2003). Efficiency or coefficient of performance (CoP) of GSHP systems have been studied experimentally, analytically and numerically (Aditya et al., 2018; Huang, 2015; Ruan, 2012; Self et al., 2013; Spitler et al., 2014), and GSHP systems are typically more efficient than conventional systems (Huang, 2015; Self et al., 2013; Spitler and Gehlin, 2015; Wu, 2009). A system with a higher CoP means that less electrical energy is required to run the system. Hence, the adoption of GSHP systems instead of conventional systems can contribute to the objective to reduce greenhouse gas (GHG) emissions.

Despite all these, the uptake for GSHP systems has been relatively limited, with factors such as finance, technology and policy having been cited as the typical barriers to adopt this technology (Karytsas and Choropanitis, 2017). Several authors have indicated that installation cost is the most difficult challenge to overcome (Karytsas and Choropanitis, 2017; Lu et al., 2017). Design methods such as hybrid GSHP (HGSH) systems have been suggested, where the lifetime costs are minimised by taking advantage of both the lower capital costs of conventional systems and the lower operational costs of GSHP systems (Aditya et al., 2019; Alavy et al., 2013; Mikhaylova et al., 2016; Nguyen et al., 2014; Cullin and Spitler, 2020; Xu, 2007). However, this hybrid system solution with the lowest lifetime costs is usually not the most optimal from the environmental perspective. GSHP systems are typically the most efficient, hence they are expected to emit the least emission compared to other heating and cooling systems.

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Nomenclature			
CoP	Coefficient of performance,		ground load, m.K/W
GHG	Greenhouse gas,	R_{10y}	Effective thermal resistance of the ground to 10 years of ground load, m.K/W
q_h	Peak hourly ground load, kW	T_g	Undisturbed ground temperature, °C
q_m	Average monthly ground load, kW	T_{ih}	Entering water temperature to GSHP in heating operation, °C
q_y	Average yearly ground load, kW	T_{ic}	Entering water temperature to GSHP in cooling operation, °C
R_b	Effective thermal resistance of the borehole, m.K/W	T_p	Temperature penalty, °C
R_{6h}	Effective thermal resistance of the ground to 6 hours of ground load, m.K/W	λ	Thermal conductivity of the ground, W/m.K
R_{1m}	Effective thermal resistance of the ground to 1 month of		

The environmental impact of GSHP systems during the operational stage has been investigated previously. The use of GSHP and HGSHP systems has been reported to reduce GHG emissions in Ontario, Canada (Nguyen et al., 2016). Other authors estimated that a 35 % reduction in GHG emissions is possible in Sweden and Switzerland (Bayer et al., 2012; Blum et al., 2010). More recent literature reveals that the life cycle assessment (LCA) method is preferred, where environmental impact is considered throughout the life cycle of the system (Lu, 2018; Saner et al., 2010; Koroneos and Nanaki, 2017; Zhou et al., 2020; Bloom and Tinjum, 2016). The LCA method considers the lifetime environmental impact from the resources needed for the raw materials, assembly, transport, operation and disposal.

These previous works suggest that HGSHP systems have the potential to be beneficial financially and environmentally. There is also some trade-off between financial and environmental savings between the users who pay the financial costs and society who usually bear the environmental costs. Hence, a multi-objective optimisation strategy is needed, where an optimal hybrid system configuration is proposed while considering both financial and environmental benefits.

This paper built on previous work by Aditya et al. (2019), where it was reported that HGSHP systems have the potential to reduce lifetime costs in Australia. In this paper, a multi-objective optimisation method is adopted where the economic and environmental performance of HGSHP systems are investigated under Australian climatic, cost and emission conditions. Based on these design parameters, a Pareto optimal approach is then utilised to find the optimum solution set that considers both financial and environmental benefits of HGSHP systems. Finally, a sensitivity analysis is conducted to investigate the impact of potential changes in those key design parameters.

2. Data and methodology

Seven major Australian cities have been chosen to represent the different climatic conditions encountered in Australia, ranging from temperate to tropical climate (Peel et al., 2007). Those cities are Adelaide, Brisbane, Cairns, Hobart, Melbourne, Perth and Sydney.

Table 1

: Description of the case study building including parameters used for EnergyPlus simulation.

Building characteristics	Value	Note
Building floor area (m ²)	150	1 living room, 2 bedrooms
Floor height (m)	3	
Number of occupants	4	
External wall U-value (W/m ² K)	0.987	Concrete wall & gypsum, including insulation
External roof U-value (W/m ² K)	0.285	Metal decking, including insulation. Flat roof
External window U-value (W/m ² K)	6.424	Glass window
Zone ventilation (air change per hour)	1	20% more than the minimum outdoor area required in Australia (0.35 L/s/m ²), AS 1668.2–2012 (Australian Standard, 1668.2., 2012)
Indoor heating thermostat set point (°C)	20	
Indoor cooling thermostat set point (°C)	22	
Occupancy		Assume all year around
Weather data		TMY file available at each location from Meteonorm (2017)

2.1. Thermal loads

The peak thermal load and hourly thermal demand at each city were simulated by using EnergyPlus (Crawley et al., 2000) for a typical 150 m² Australian residential dwelling. The parameters used for this simulation is provided in Table 1. For simplicity, the same building is assumed for each location. However, the climatic condition at each location is different, resulting in the buildings to have different peak heating and cooling loads as well as annual thermal demands. The undisturbed ground temperature (T_g) at shallow depth (less than 200 m) can be assumed as the average local air temperature plus 2 °C, as described in IGSHPA (2009). The resulting thermal load, total annual energy demand and undisturbed ground temperature in each of the Australian cities are summarised in Table 2.

2.2. Heating and cooling options

The previous survey by the Australian Bureau of Statistics (2014) indicated that 38 % and 30 % of households in Australia use electricity and gas, respectively, for their heating requirements, while for cooling, 49 % of households use electricity. Due to both heating and cooling requirements, Australians tend to use a reverse cycle air conditioner (RCAC) to satisfy heating and cooling with a single system. Therefore, five heating and cooling options are considered in this paper:

- 1 Heating and cooling by an RCAC;
- 2 Heating with a gas furnace and cooling by an RCAC;
- 3 Heating and cooling with a GSHP;
- 4 Heating and cooling by an HGSHP system (HGSHP1) with a GSHP and an RCAC;
- 5 Heating and cooling by an HGSHP system (HGSHP2) with a GSHP, a gas furnace for heating and an RCAC for cooling.

The CoPs of GSHP and RCAC system typically vary throughout the year. The entering water temperature (EWT) to the GSHP determines its CoP, while the CoP of RCAC system is affected by the outside air

Table 2
: Ground temperatures, peak heating and cooling loads, average seasonal CoP of RCAC and GSHP system.

	Estimated average T _g at shallow depth (°C)	Estimated peak heating/cooling load (kW)	Annual heating/cooling demand (kWh)	SCoP of RCAC (-)	SCoP of GSHP (-)
Adelaide	18.7	7.4/6.7	12.5/3.2	2.5	4.6
Brisbane	22.2	7.2/7.2	5.3/8.3	2.6	4.7
Cairns	26.5	3.3/9.0	0.4/22.0	2.5	4.2
Hobart	12.9	8.6/5.6	20.7/0.6	2.5	4.2
Melbourne	16.5	8.4/5.5	18.2/2.0	2.5	4.5
Perth	19.9	7.8/8.1	8.8/5.3	2.6	4.7
Sydney	20.1	5.8/7.3	6.4/5.5	2.6	4.7

temperature. Hence, both systems are expected to have different CoP due to the differences in climatic conditions in each city. In this case study, a high-performance GSHP (Water Furnace NSKW06) and RCAC unit (Fujitsu AOTG30KMTA) were selected. Those units are available off the shelf and the manufacturers provided a detailed datasheet which was utilised to compute the hourly CoPs of both systems. The hourly CoP of the GSHP system was calculated by using a methodology from Weeratunge et al. (2018), where the hourly ground temperature and EWT were simulated and used to determine the hourly CoPs at each location. The hourly CoP of the RCAC system was much simpler to compute as they are only dependent on the outside air temperature at each location. Table 2 indicates these CoP variation between each city where the hourly CoPs are averaged and referred as a seasonal CoP (SCoP). The efficiency of a gas furnace is assumed as a constant 0.9 for simplicity as this value represents a constant rate of gas combustion.

The design length (L_{GHE}) for the ground heat exchanger (GHE) is calculated based on the ASHRAE design approach shown in Equation 1 (Philippe et al., 2010), with the design parameters defined in Table 3.

$$L_{GHE} = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_c R_{6h}}{\frac{(T_i + T_o)}{2} - (T_g + T_p)} \quad (1)$$

where each factor is defined in the list of notation. It is important to recognise that geological parameters such as ground thermal conductivity (λ) can vary across the cities considered here. For the base case, 2.5 W/m.K is assumed as the base λ , but this value is varied in Section 3.3 for a sensitivity analysis.

The HGSHP systems here consider the proportion of heating and cooling loads provided by GSHP and conventional systems. This proportion is referred to as the *shave factor*. In this paper, the heating and cooling shave factors are varied from 0% to 100 % with a step size of 2 % to cover a range of configurations. The 0% shave factors refer to conventional systems, while 100 % shave factors refer to GSHP systems. The shave factors between 0% and 100 % represent hybrid systems combination of both RCAC and GSHP systems. A shave factor of 60 % means the GSHP system provides 60% of the peak load, while the

conventional system provides the remaining 40 %.

2.3. Cost and emission parameters

In this paper, life cycle analysis is used to compare the total lifetime costs and emissions of all the heating and cooling systems. All the systems are assumed to be installed and used for 20 years. It is further assumed that a GSHP has a lifespan of 20 years while an RCAC and a gas furnace each have a lifespan of 10 years, based on Lu et al. (2017) and Lu and Narsilio (2019). This means that after 10 years, a new RCAC and gas furnace need to be installed to replace the old one, which incurs additional capital costs and GHG emissions. All the analysis is in Australian dollars (A\$), where currently one A\$ is US\$ 0.72.

The net present cost method is selected as the principal economic indicator for all the heating and cooling systems considered. The NPC can be calculated using Eq. 2:

$$NPC = \sum_{t=1}^{20} \frac{C_t}{(1+r)^t} \quad (2)$$

where C_t represents the cash outflow at time t in years, which can be a capital cost or an operating cost. This cost at time t will be discounted back at interest rate r (3.5 %, see Table 4) over a 20-year design life of the system. The capital costs include the cost to install the systems at the start and, if necessary, the cost to replace the systems at the 10-year mark. For GSHP and HGSHS systems, there is also an initial cost to install the GHEs. The operational costs are simply the cost to operate the systems for 20 years. All assumed parameters for cost calculations are presented in Table 4, while the unit prices for electricity and gas are presented in Table 5, based on various major local energy retailers (Aurora Energy, 2017; Origin Energy, 2017; Synergy, 2017).

A similar life cycle method is considered for the environmental assessment in this paper. Initial activities such as manufacturing, transport and installation processes can cause some GHG emissions. Work by others has indicated that these initial emissions (IE) are relatively low compared to the lifetime GHG emissions (LGE) generated through the

Table 3
: Parameters used for sizing of GHEs.

Design parameter (units)	Description	Value
q_h, q_m, q_y (kW)	Peak hourly, monthly average and yearly average ground loads	Calculated based on building thermal demand, heating and cooling shave factors, and COP of GSHP
R_b (m.K/W)	Effective thermal resistance of the borehole	0.103
λ (W/m.K)	Ground thermal conductivity, used to calculate R_{6h}, R_{1m} and R_{10y}	2.5
R_{6h} (m.K/W)	Effective thermal resistance of the ground to 6 hours of ground load	0.106
R_{1m} (m.K/W)	Effective thermal resistance of the ground to 1 month of ground load	0.146
R_{10y} (m.K/W)	Effective thermal resistance of the ground to 10 years of ground load	0.153
T_g (°C)	Undisturbed ground temperature at shallow depths	Listed in Table 2
$T_{i,h}$ (°C)	EWT to GSHP in heating operation	$T_g - 5.5$ °C ($T_g - 10$ °F)
$T_{i,c}$ (°C)	EWT to GSHP in cooling operation	$T_g + 11.1$ °C ($T_g + 20$ °F)
T_p (°C)	Temperature penalty	0 (GHE is thermally independent)

Table 4
: Parameters assumed for cost comparisons (based on Lu (2018)).

Parameter (units)	Value	Note
Cost of drilling (A\$/m)	80	Borehole installation
Cost of GSHP (A\$/kW)	2000	Equipment and installation of the system
Cost of gas furnace (A\$/kW)	500	Equipment and installation of the system
Cost of RCAC (A\$/kW)	1000	Equipment and installation of the system
Emissions for drilling (kgCO ₂ e/m)	7.8	Including HDPE pipes, drilling and grouting
Emissions for GSHP (kgCO ₂ e/kW)	69	Including material and manufacturing
Emissions for gas furnace (kgCO ₂ e/kW)	1.4	Including material and manufacturing
Emissions for RCAC (kgCO ₂ e/kW)	69	Including material and manufacturing
Electricity inflation rate (%)	6.2	
Gas inflation rate (%)	6.14	
Discount rate, r (%)	3.5	
Lifespan of GSHP system (years)	20	
Lifespan of gas furnace and of RCAC (years)	10	
Replacement of gas furnace and RCAC	Every 10 years	
Design life (years)	20	

operational emissions (OE) stage of the heating and cooling systems (Lu, 2018; Saner et al., 2010). We hypothesise that these IE would be a small percentage compared to the LGE as the electricity emission factor in Australia is quite high. Nevertheless, we include these IE in the analysis for completeness, including additional IE required when RCAC or gas system is replaced at the 10-year mark. The LGE in each city can be calculated using Eq. 3, and all the input parameters used in this calculation are presented in Table 4 and Table 5. IE [kgCO₂e] is the sum of the initial emissions for drilling and the initial emission of the relevant equipment (GSHP or gas furnace or RCAC). OE [kgCO₂e] is the annual operational emissions, which is the calculated annual emissions [kWh] multiplied by the emission factor [kgCO₂e/kWh] for electricity or gas.

$$LGE = IE + \sum_{t=1}^{20} OE_t \quad (3)$$

It is important to recognise that the electricity emission factor is different in each city, with Hobart having the cleanest electricity (0.14 kgCO₂e/kWh), where most of the electricity is generated by a renewable source such as hydro. In contrast, the highest emission-intensive electricity is in Melbourne (1.08 kg CO₂e/kWh), where most of the electricity is generated from brown coal. There is only one emission factor value for gas as the value is based on the emissions generated from gas combustion as opposed to several emission factors for electricity in each Australian state as the value depends on the combustion generated from a distinct fuel (coal, gas, renewable etc) mix.

Based on using the above parameters, the NPC and LGE for all of the heating and cooling systems can then be calculated for each heating and cooling shave factor combination for the seven cities considered in this study.

2.4. Pareto optimal approach

The Pareto optimal approach was originally developed in the economics field (Pareto, 1906), but it has been extended into other areas,

Table 5
: Price and unit emission factors for electricity and gas for all the cities considered.

	Electricity price (c/kWh)	Gas price (c/kWh)	Electricity/gas price ratio (-)	Electricity emission factor (kgCO ₂ e/kWh)	Gas emission factor (kgCO ₂ e/kWh)	Electricity/gas emission ratio (-)
Adelaide	31.3	13.0	2.4	0.49	0.185	2.65
Brisbane	22.0	10.6	2.1	0.79		4.27
Cairns	22.0	10.6	2.1	0.79		4.27
Hobart	20.2	12.6	1.6	0.14		0.76
Melbourne	27.6	9.4	2.9	1.08		5.83
Perth	27.2	10.3	2.6	0.70		3.78
Sydney	23.8	12.6	1.9	0.83		4.49

including GSHP systems design (Huang et al., 2015; Sayyaadi and Amlashi, 2010; Sayyaadi et al., 2009; Sayyaadi and Nejatolahi, 2011). Marler and Arora (2004) suggested that for a multi-objective optimisation method, there may not be a single global solution and a solution set may be required. In this paper, the design process for HGSHP systems considers both NPC and LGE for different heating and cooling shave factor combinations.

The solution set that is considered as the *Pareto optimal* is the set such that there does not exist another shave factor combination with lower NPC or LGE. For example, each point in Fig. 1 represents the NPCs and LGEs for all shave factor combinations for HGSHP1 in Sydney. The thicker black line represents the Pareto optimum solution set, where points A and C are included in the solution set. Point B is not Pareto optimal as there exist other possible shave factor combinations with lower NPC and the same LGE as point B (such as point A) and there exist other possible shave factor combinations with lower LGE and the same NPC of point B (such as point C). Therefore, it is considered generally efficient to size GSHP systems at any point along this Pareto optimum solution to minimise both NPC and LGE.

It should be noted that point A is considered as the solution with the lowest NPC, while point C is considered the solution with the lowest LGE. It is understandable that most homeowners would choose to design their HGSHP systems at point A with the lowest lifetime costs to install and operate the heating and cooling system. In contrast, the government (and society) might want to encourage homeowners to minimise their LGE by choosing point C. This mismatched incentive creates a financial and emission gap between point A and point C. Depending on their environmental objectives, the government can overcome this NPC gap (or part of it) by providing various financial incentives, such as through carbon taxes, green incentives or tax breaks for going green. These incentives can potentially encourage homeowners to move away from point A (along the Pareto optimum solution) to reduce their lifetime GHG emissions.

The single most optimum point from this solution set, however, will need to be decided by the relevant stakeholders given the weighted

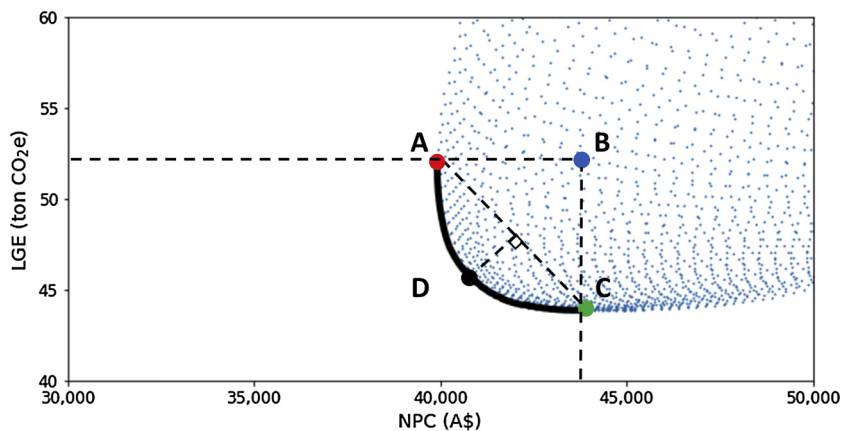


Fig. 1. Example of a Pareto optimum solution. Points A and C are Pareto optimal, while point B is not.

importance of NPCs and LGEs. This single point is based on a range of factors and most likely is unique for each location and scenario. One method about how to decide this point is presented by Sayyaadi et al. (2009) and Huang et al. (2015), who have suggested an equal-weighted coefficient to find a single optimum point from a Pareto solution set. This optimum point was suggested as the point that is mathematically defined as the ‘elbow of the curve’ or the point with the maximum curvature. Satopaa et al. (2011) presented an algorithm to find this optimum point (point D in Fig. 1), where this is the point with the longest perpendicular distance to the straight-line AC. Note that this point is close to, but not always is, the median of the Pareto optimum solution set as the location of this point depends on the rate of change of the curve itself. For simplicity, this method is also adopted in this paper and referred to as the equal-weighted (EW) solution. Having a single point also allows comparisons between various scenarios.

Ultimately, it is up to the homeowners to decide the shave factor proportion between GSHP and conventional systems. After all, they are the ones paying the installation and operational costs, and hence they should be the most important decision-maker. The results presented here may allow designers and engineers to let homeowners to be informed and make a decision. Homeowners can install at point A if they want to minimise costs. Alternatively, point C may be preferred if they want to minimise emissions and be green. Otherwise, they can install at point D for example, if they want to both contribute to society with minimal extra financial costs. Other points are also an option depending

on their criteria.

3. Results and discussions

In this section, results corresponding to Sydney, Hobart and Cairns are chosen to represent a balanced climate, a heating-dominant climate, and a cooling-dominant climate, respectively.

3.1. Pareto optimum solution for HGSHp systems under base case conditions

Fig. 2 presents the NPCs and LGEs for each shave factor combinations for HGSHp1 and HGSHp2 in Sydney. The Pareto optimum solutions are represented by the black lines. Furthermore, the lowest NPC solution, the lowest LGE solution and the EW solution are provided. For HGSHp1, the lowest NPC for the 20-year lifespan of the system is approximately A\$40,000 with an LGE of 52 ton CO₂e. In contrast, if the HGSHp1 system is designed to minimise the LGE, the optimum design has an NPC of approximately A\$44,000 but with an LGE of 44 ton CO₂e. This 8 ton CO₂e savings seems low, but this value represents 15 % of the total emissions (8/52). It is important to recognise that a 15 % lifetime emission reduction is equivalent to over three year’s worth of emissions caused by the heating and cooling usage in this house. The EW solution for HGSHp1 in Sydney has an NPC of A\$41,000 and an LGE of 44 ton CO₂e.

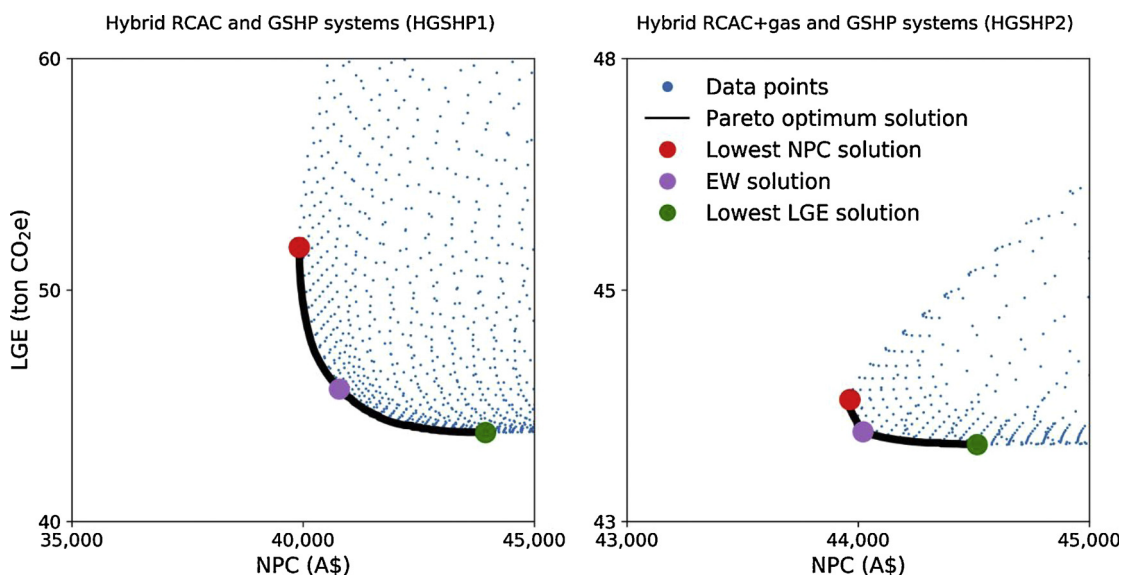


Fig. 2. Pareto optimum solutions for HGSHp1 and HGSHp2 in Sydney.

The Pareto optimum solutions for HGSH2 systems in Sydney offer an interesting case where the lowest NPC, the lowest LGE and the EW solution have similar NPCs and LGEs of \$44,000 and 44 ton CO₂e. Overall, the difference between the lowest NPC and the lowest LGE solution is a lifetime cost and emission of \$500 and 0.5 ton CO₂e respectively. This will be discussed further below.

The results presented in Fig. 2 offers an insight into the potential usage of HGSH1 and HGSH2 under Sydney’s climatic conditions to minimise the NPCs and the LGEs. However, further examination is needed to determine how much of the total peak load proportion needs to be provided by GSHP and conventional systems, which is commonly referred to as a *shave factor*. The shave factors need to be decided prior to the construction stage to achieve the desired level of NPCs and LGEs. To do this, the corresponding heating and cooling shave factor is presented in Fig. 3 to complement the Pareto optimum solution set results presented earlier. The bottom left corners of the plots in Fig. 3 represent a 0% shave factor or effectively conventional systems. The top right corners of the plots represent a 100 % shave factor or effectively GSHP systems. The points in between represent different shave factor combinations for each HGSH system in Sydney. In this plot, the Pareto optimum solution is presented based on the relevant heating and cooling shave factors. The lowest NPC solution, the lowest LGE solution, and the EW solution are also provided.

GSHP system designers need the heating and cooling shave factor information presented in Fig. 3 as they cannot design a GSHP system by aiming for the lifetime cost and emission values shown earlier. In this case, if homeowners request an HGSH1 system with the lowest lifetime costs, then designers are recommended to size the system for 32 % heating and cooling shave factors. Similarly, to minimise the lifetime emissions, it is best to utilise a hybrid system with the GSHP component is designed to meet 90 % of the peak heating and cooling load. The EW solution occurs at 52 % heating and cooling shave factors.

The Pareto optimum solution for HGSH1 system shown in Fig. 3 is almost exactly at the 45-degree line (i.e., equal heating and cooling shave factors). This suggests that both heating and cooling shave factors have some effect on the Pareto optimum solutions since buildings require both heating and cooling in Sydney. The Pareto optimum solutions sets also indicate a tradeoff between costs and efficiency. One of the major barriers for GSHP system adoption is the capital costs to install the GHE. Utilising a hybrid system enables users to take advantage of both the lower capital cost of a conventional system and the lower operational cost of a GSHP system. In this case, the system with the lowest NPC utilises a GSHP system, which is sized to meet 32 % of the

peak load needed in Sydney. A smaller GSHP system capacity means less GHE length required. This system is further supported by a conventional system, which is cheaper to install, but less efficient. The GSHP system able to satisfy around 75 % of the annual thermal demand with this setup.

In contrast, the lowest LGE solution is for an HGSH1 system where the GSHP system is designed to provide around 90 % of the peak heating and cooling load. It is important to note that at this point, this system is effectively a full GSHP system as 99 % of the annual thermal demand can be satisfied. This makes sense since the average hourly CoP of the GSHP system is higher than the RCAC system. A more efficient system requires less electricity, thus resulting in lower lifetime emissions.

Another interesting observation is that the lowest LGE solution is not the GSHP system itself but an HGSH1 system at a 90 % heating and cooling shave factors as outlined above. At this point, the GSHP is sized for 5.3 and 6.3 kW heating and cooling load respectively. Additional RCAC system is needed when the building requires the peak thermal demand of 5.8 and 7.3 kW of heating and cooling respectively. Based on the weather data, there are only 23 hours of the year (0.3 %) when this happens. This means that the additional electricity savings and emissions for utilising a more efficient GSHP system during these hours are minimal. In contrast, a full GSHP system would require a bigger GSHP unit and a longer GHE length, which means higher initial costs and emissions. Overall, this results in a scenario where the lowest LGE solution has both lower NPC and LGE compared to a full GSHP system.

The Pareto optimum solution set presented for HGSH2 systems in Fig. 3 is relatively narrow compared to the solution set for HGSH1 system. This suggests that the hybrid component mix between the lowest NPC and LGE solutions are quite similar. The lowest NPC solution is at 60 % heating and cooling shave factors where the GSHP system is able to provide 96 % of the annual thermal demand. The lowest LGE solution is at 82 % and 86 % heating and cooling shave factors where the GSHP system is able to meet 99 % of the annual thermal demand. Since the GSHP system provides most of the annual thermal demand for both scenarios for the HGSH2 system, hence it is not surprising that the lifetime costs and emissions for these scenarios are relatively similar.

HGSH2 system offers the possibility to provide heating either by using electricity through a GSHP system or by using gas through a gas furnace. The cheaper option depends on the relative efficiency of both systems and the relative price of electricity and gas. In Sydney, the

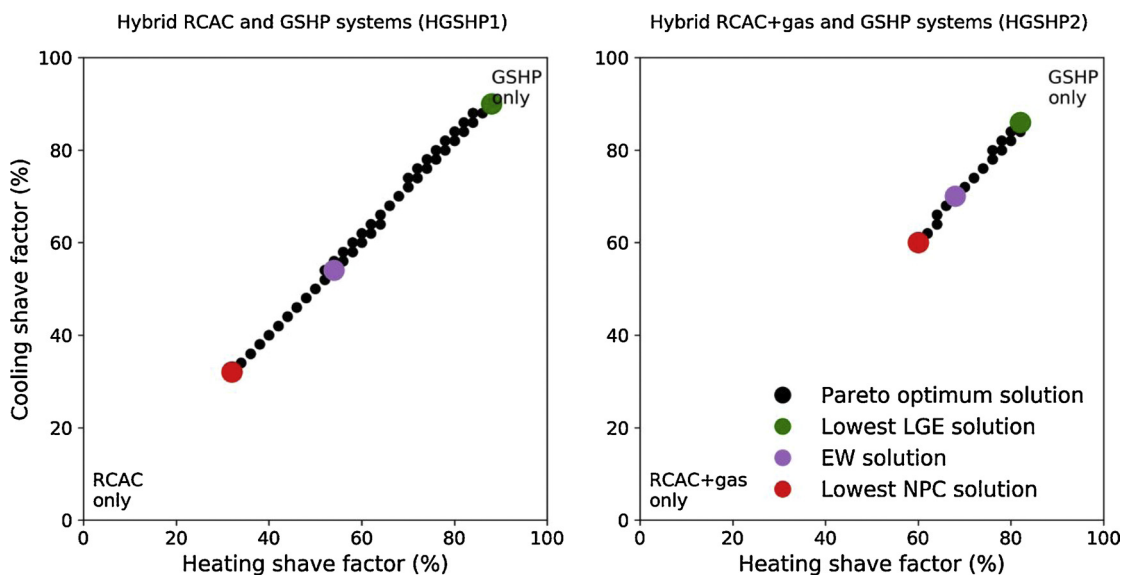


Fig. 3. Heating and cooling shave factors corresponding to the Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney.

relative efficiency between GSHP and gas furnace is 5.2 (CoP of GSHP system is 4.7 divided by efficiency of 0.9 for a gas furnace). However, electricity is only 1.9 times more expensive than gas. This means that in HGSH2 system, heating with a GSHP system is financially preferred compared to heating with a gas furnace as the alternative. This explains that the lowest NPC solution for HGSH2 system has a higher heating and cooling shave factor (60 %) than in HGSH1 system (32 %).

This observation suggests that when gas is available as a substitute fuel source for a heating system, then the analysis needs to be considered on a case-by-case basis. This substitution effect on the NPCs and LGEs can be complex, where they can depend on the climates, fuel costs, fuel emission factors and the efficiency of the relevant heating and cooling systems in each location.

The analysis is then repeated for a heating-dominant climate in Hobart. The Pareto optimum curve in Hobart for HGSH1 and HGSH2 is presented in Fig. 4. For HGSH1, the lowest NPC for the 20-year lifespan of the system is approximately A\$61,000 with an LGE of 20 ton CO₂e. Fig. 5 indicates that this lowest NPC point occurs when the HGSH1 system is sized for 24 % and 36 % heating and cooling shave factors, respectively. It should be noted that this cooling shave factor is practically irrelevant as there is a minimal need for cooling in Hobart (0.6 MW h annually). In this scenario, the GSHP system only able to meet 60 % of the annual thermal demand. Despite that, the GSHP is sized to meet a small proportion of the peak heating load (2 kW from a peak of 8.4 kW). Since Hobart is highly heating dominant, then providing the full heating load with the GSHP system would result in a significantly longer GHE length and much higher installation costs. Therefore, a greater proportion of RCAC system is preferred if the goal is to minimise costs.

In contrast, if HGSH1 is designed to minimise the LGE, then it has an NPC of A\$66,000 and an LGE of 17 ton CO₂e. This solution requires the GSHP system to meet 78 % of the peak heating load, but able to meet 99 % of the annual energy demand. The EW solution has an NPC of A\$62,000 and an LGE of 18 ton CO₂e, where the GSHP needs to be sized to meet 46 % of the peak heating load (4 kW).

A similar, but shorter, range of Pareto optimum solutions can be observed for HGSH2 systems in Hobart. The lowest NPC, the lowest LGE and the EW solution in Fig. 4 have NPCs between A\$62,000 and A\$65,000 while LGE between 17 and 18 ton CO₂e. The price and emission ratio of electricity and gas is even smaller in Hobart (1.6) compared to the same ratio in Sydney (1.9). However, the efficiency ratio between GSHP system and gas furnace in Hobart is smaller than in Sydney since GSHP system in Hobart operates less efficiently

throughout the whole year due to the high heating dominant climates in Hobart. Despite this GSHP is still a much more efficient system compared to a gas furnace, which results in a very narrow Pareto optimum solution range as shown in Fig. 5. The lowest NPC, EW and lowest LGE solution requires 64 %, 72 % and 84 % heating shave factor respectively.

The Pareto optimum solution for HGSH1 in Cairns is presented in Fig. 6, along with the corresponding heating and cooling shave factor combinations. Only the result for HGSH1 is presented here as Cairns requires a very low heating requirement of 0.4 MW h. Hence, a gas furnace or an HGSH2 system is not needed. For HGSH1, the lowest NPC for the 20-year lifespan of the system is approximately A\$66,000 with total GHG emissions of 100 ton CO₂e. This optimised point is at 38 % cooling shave factor. Although heating shave factors are used in this analysis, they are practically irrelevant due to the minimal heating need in Cairns.

If HGSH1 is designed to minimise the LGE, then it has an NPC of A\$70,000 with a much lower LGE of 87 ton CO₂e, and at this point, it is practically a GSHP system since the GSHP is sized to meet 92 % of the peak cooling load and able to meet 99 % of the annual thermal demand.

The EW solution has an NPC of A\$67,000 and an LGE of 90 ton CO₂e. For this solution, the GSHP needs to be sized to meet 60 % of the peak cooling load. This EW solution offers an interesting decision-making scenario for homeowners. In comparison to the lowest NPC solution, this EW solution can reduce the lifetime emissions by 10 ton CO₂e (10 %), but only an additional A\$1000 (2%) is needed to make this happens.

This section has demonstrated the potential to optimise HGSH2 systems considering the trade-off between their lifetime costs and emissions. The single most optimum point from this solution set, however, will need to be decided by the relevant stakeholders given the relevant weighted importance of both variables.

An HGSH1 system typically has different shave factor combinations to represent a design which has the lowest lifetime costs and emissions. HGSH2 offers a slightly more interesting case where there is a trade-off between the usage of gas and electricity. In this scenario, the relative price ratio between electricity and gas, the electricity-to-gas-emission factor ratio, and the efficiency of the heating and cooling systems can play some effect. This suggests the importance of investigating this on a case-by-case basis. For this reason, the next section will investigate the potential impact if there are some changes to the key parameters considered in this base case.

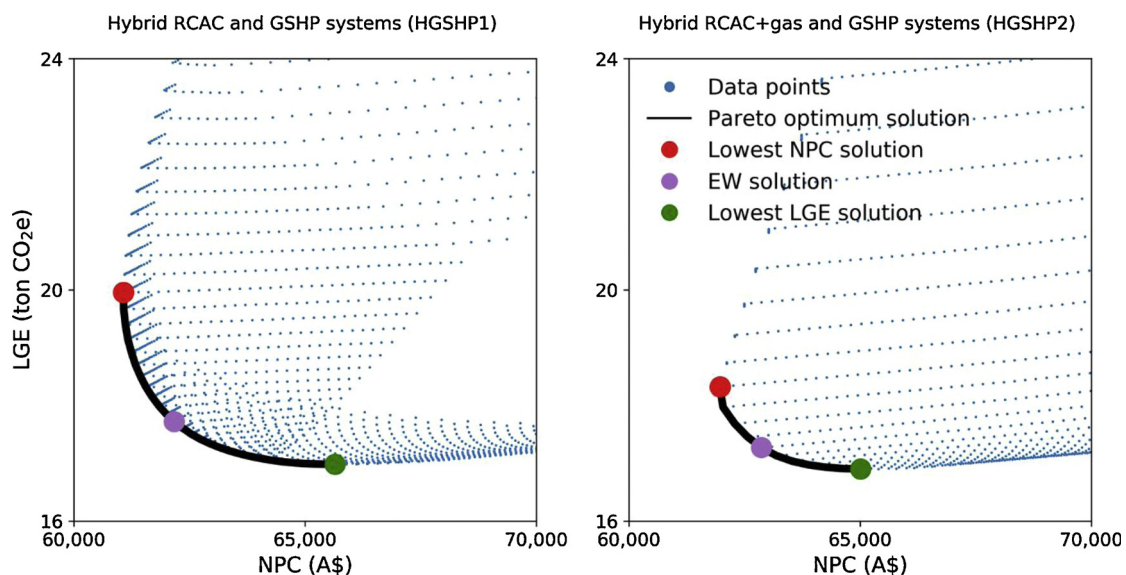


Fig. 4. Pareto optimum solutions for HGSH1 and HGSH2 in Hobart.

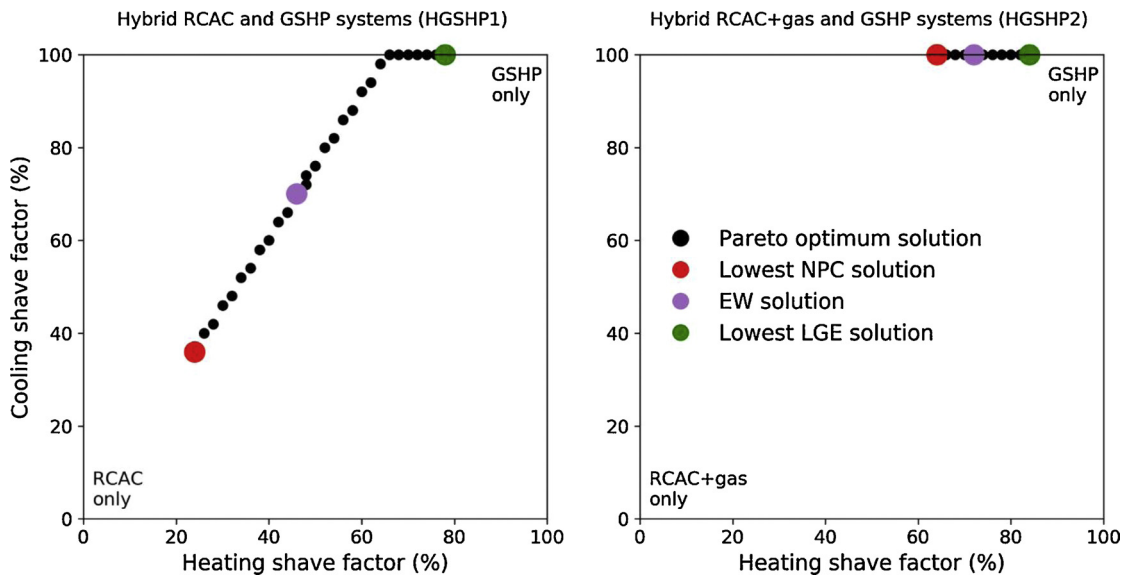


Fig. 5. Heating and cooling shave factors corresponding to the Pareto optimum solutions for HGSH1 and HGSH2 systems in Hobart.

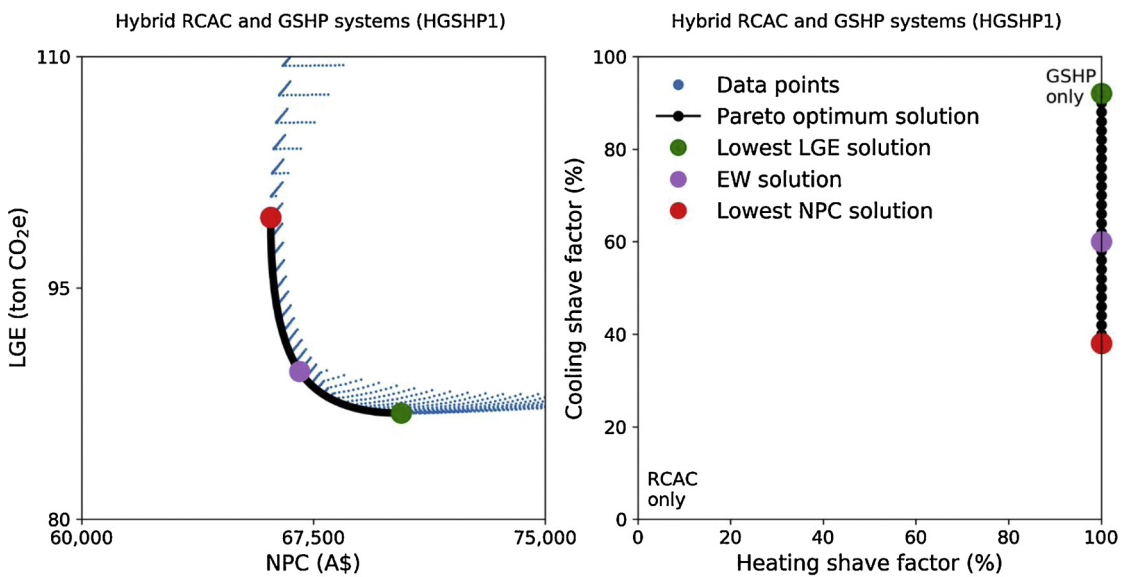


Fig. 6. Pareto optimum solutions and their corresponding heating and cooling shave factors for HGSH1 systems in Cairns.

3.2. Impact of changes in drilling cost for GHEs

The analyses presented in the previous sections were conducted with a GHE drilling cost of A\$80/m, as typically found in Australia (Lu et al., 2017). In this section, the GHE drilling costs are adjusted to A\$50/m, A\$100/m and A\$150/m. The lowest cost reflects costs in a more competitive and mature GSHP system industry, while the two highest costs reflect less favourable conditions where, for example, more difficult ground conditions are encountered. The values of all other parameters have been maintained.

Fig. 7 presents the Pareto optimum solutions for HGSH1 and HGSH2 in Sydney, Hobart and Cairns with various GHE drilling costs. An increase in drilling costs results in the Pareto optimum curve shifting to the right. Furthermore, the range of the Pareto optimum curve also widens, especially for HGSH1 systems.

The Pareto optimum solution is mostly governed by the costs required and emissions generated during the operational stage of the systems as the costs and emissions add up over 20 years life-span of the systems. Since the relative efficiency of a GSHP system to an RCAC

system is smaller than a GSHP system to a gas furnace, then an increase in capital costs (as drilling cost increases) should have more effect in an HGSH1 system compared to an HGSH2 system. This is represented by the significant change in the possible range of Pareto optimum solutions in HGSH1, whereas only small changes occur in HGSH2, as shown in Fig. 7. This change reflects that, as drilling cost increases, the RCAC system becomes more competitive, and hence a higher usage proportion is desired in the hybrid system mix. In fact, for HGSH1 system, the lowest NPC solution in all three cities when the drilling cost is A\$150/m is effectively the conventional RCAC system. But, this is not the case for HGSH2 system at this A\$150/m drilling cost scenario. A more significant increase in drilling cost is required for the HGSH2 system to have a more noticeable effect on the Pareto optimum curve for HGSH2.

In Fig. 7, as drilling cost is increased, the lowest NPC solutions experience an increase in both their NPCs and LGEs. It should be noted that each of these lowest NPC solutions refers to different heating and cooling shave factor combinations. As GHE drilling cost increases, GSHP systems become more expensive, and thus a greater proportion of

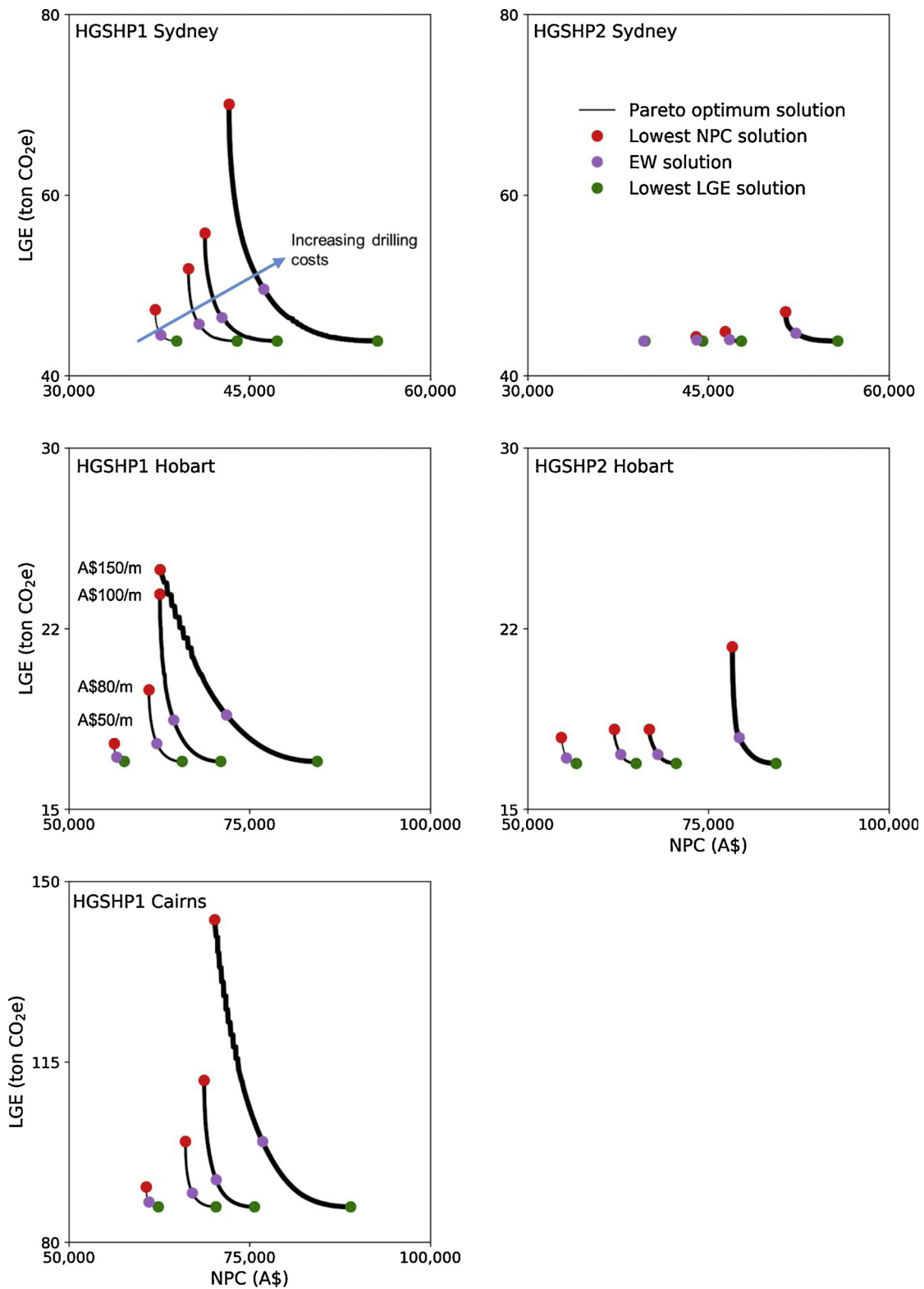


Fig. 7. Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney, Hobart and Cairns with a drilling cost of A\$50/m, A\$80/m A\$100/m and A\$150/m.

conventional systems is preferred. Since a conventional system is less efficient than a GSHP system, then more electricity is required to run the system, thus resulting in higher lifetime costs and emissions.

In contrast, when the drilling cost is increased, only the NPC changes for the lowest LGE solution, while the LGE values remain unchanged. This indicates higher lifetime costs (reflecting higher installation costs) while the total emissions stay the same. This makes

sense as an increase in drilling costs should not change the lifetime emissions as the emissions depend on energy consumption. As before, all these lowest LGE solutions are effectively the GSHP systems at each location.

3.3. Impact of changes in thermal conductivity of the ground

In this section, various ground thermal conductivity values (λ) are investigated, with the λ values varying from 0.7 to 2.5 W/m.K. These values have been chosen to represent typical soils such as clay, silt and sand; both in saturated and unsaturated conditions as measured by Bose (1989). Other parameters are kept the same in this section.

A decrease in λ causes an increase in GHE length and in turn is expected to increase capital costs to install GSHP and HGSHS systems. Fig. 8 presents the Pareto optimum solutions for HGSHS1 and HGSHS2 in Sydney, Hobart and Cairns when the λ is decreased. Overall, decreasing λ causes the Pareto optimum solutions curve to shift to the right, indicating higher lifetime costs and emissions generated by the systems. The increase in costs is not too significant since a decrease in λ .

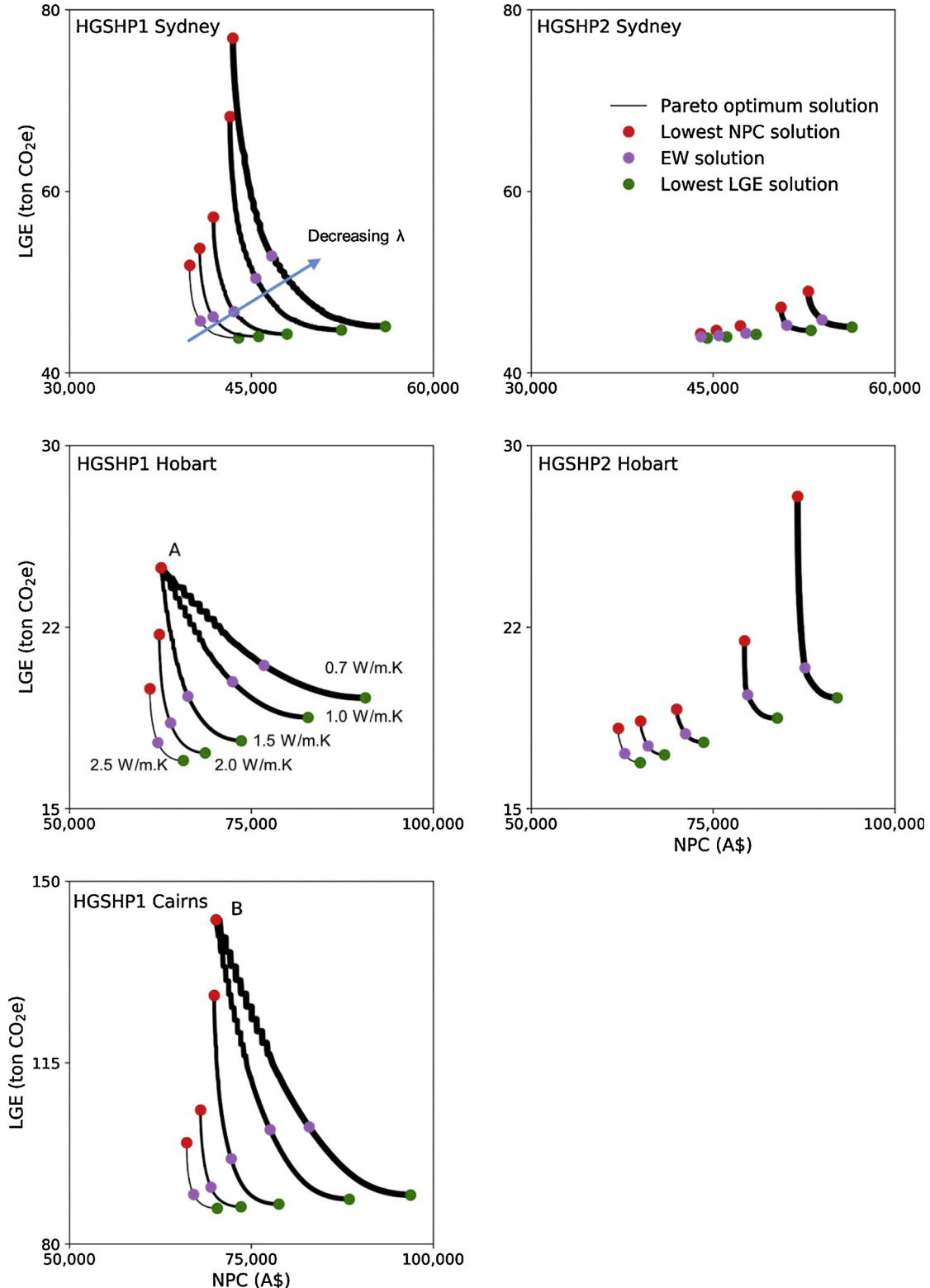


Fig. 8. Pareto optimum solutions for HGSHS1 and HGSHS2 systems in Sydney, Hobart and Cairns when the ground thermal conductivity (λ) decreases.

only affects the capital cost component of the system and this costs increase will then distributed throughout the lifetime of the systems.

The lowest LGE solutions shift to the right as λ decreases, which indicates an increase in NPCs and LGEs. The increase in the LGEs is minimal, except for the case in Hobart. A longer GHE length means more emissions generated during the drilling process. For the cases in Sydney and Cairns, the emissions generated through the operation of the systems are much more significant due to the high electricity emission factor at those locations. This means that the increase in drilling-related emissions is relatively minor in Sydney and Cairns. In contrast, the electricity emission factor in Hobart is significantly lower, which means that any changes in drilling-related emissions would contribute to the lifetime emissions more significantly.

Furthermore, the corresponding heating and cooling shave factors for the lowest LGE solutions also decreases as λ increases. As drilling-related emission increases, it is logical that the hybrid system with the lowest lifetime emissions would need a shorter GHE length, which causes a higher proportion of conventional system is required. For example, for HGSH1 system in Hobart, the lowest LGE solution when λ is 2.5 W/m.K has a corresponding heating shave factor of 78 %. At this point the GSHP system component can provide 99 % of the annual thermal demand. If λ is 0.7 W/m.K, then the HGSH1 component has a GSHP with a heating shave factor of 68 % and able to provide 98 % of the annual thermal demand.

For the lowest NPC solutions, decreasing λ causes both the NPCs and the LGEs to increase, where the increase in the LGEs is much more significant as λ decreases, especially for the HGSH1 system. The increase in GHE length needed means that a higher proportion of conventional systems is preferred to be more cost-efficient in the hybrid configuration. Therefore, as λ decreases, the lowest NPC solution corresponds to lower heating and cooling shave factors. In fact, this lowest NPC solution is the conventional system (RCAC) for HGSH1 in Hobart and Cairns when λ has decreased to 1.5 W/m.K and 1 W/m.K, respectively. This is represented by points A and B in Fig. 8. This means that at such a point, the GHE installation costs have become too expensive due to the significantly long GHE requirements caused by poor ground thermal conductivity. Hence, it is preferred to install conventional systems without any GHEs. For this reason, a further decrease in λ has no effect as GHE is not required and an RCAC system is used at this point. The effect described above is less apparent for the HGSH2 system since a GSHP system is significantly more efficient than a gas furnace system. Hence, only a drastic decrease in λ (such as to 0.7 W/m.K) affects the range of possible Pareto optimum solutions such as for the HGSH2 system in Hobart.

3.4. Impact of changes in energy prices

The last two sections have presented the effect of potential changes in capital costs of the system. In this section, potential changes in operational cost are investigated by varying energy prices. Energy prices

may change depending on the market forces in the future energy sector. It is difficult to gauge future energy prices in Australia due to the large dependency on fossil fuel here. The future energy prices may increase due to fossil fuel scarcity but may decrease if a greater portion of renewable energy is used instead. For this reason, the electricity and gas prices presented in Table 5 are decreased by 50 % and increased by 50 % and 100 % to potentially reflect these changes. The effect of these energy price changes is investigated when the energy prices are changed individually or together. Changing these prices individually also changes the energy price ratio between electricity and gas, whereas changing these prices together will keep this ratio unchanged.

Fig. 9 presents the case for HGSH1 system when the energy price is changed. Since HGSH1 system only uses electricity, then changing the energy price together or individually should result in the same effect as the price of gas is irrelevant for HGSH1 system. It can be observed in Fig. 9 that the Pareto optimum solution curve shifts to the right, indicating higher lifetime costs. Furthermore, the curve also gets narrower as the energy price is increased in each city. In the HGSH1 system, increasing the price of electricity represents a direct trade-off between GSHP and RCAC systems since both require electricity to run. A more efficient GSHP system is preferred when the energy price is increased. In contrast, the RCAC system is preferred when the energy price is low.

For the same reason, the lowest NPC solution corresponds to a different hybrid system mix for each price scenario at each city. When the energy price is low, the lowest NPC solution is the RCAC system at each location. This also explains that this lowest NPC solution has high emissions as RCAC system requires more electricity consumption. As energy prices increases, the lowest NPC value refers to a higher proportion of GSHP system usage. For example, when the energy prices are doubled in Sydney, the lowest NPC in HGSH1 system configuration has the GSHP unit sized to meet 52 % of the peak heating and cooling load but able to meet 93 % of the annual thermal demand. This 52 % shave factor is significantly higher compared to the 32 % shave factor in the base case.

The lowest LGE solution for each scenario is effectively the GSHP system as described in previous sections. The corresponding heating and cooling shave factors for this lowest LGE solution remains unchanged even when the energy price is changed.

The effect of changing energy price is more complex in the HGSH2 system due to the possible substitution effect between electricity and gas. Furthermore, the effect may be different when the energy prices are changed individually or together. Hobart is chosen to show the results since it is heating-dominant and expected to be more price-sensitive to this substitution effect when the gas price is changed.

The effect of changing energy prices for HGSH2 system in Hobart is presented in Fig. 10. The impact of changing both prices simultaneously is similar to that of HGSH1 systems, where the Pareto optimum solution shifts to the right, indicating higher lifetime costs. However, changing the energy price simultaneously has a much smaller

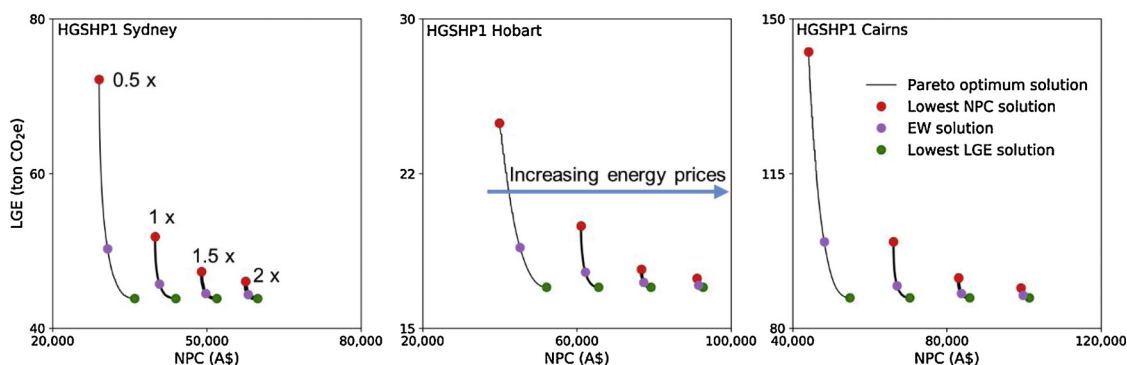


Fig. 9. Pareto optimum solutions for HGSH1 systems in Sydney, Hobart and Cairns when both energy prices are multiplied by 0.5, 1, 1.5 and 2.

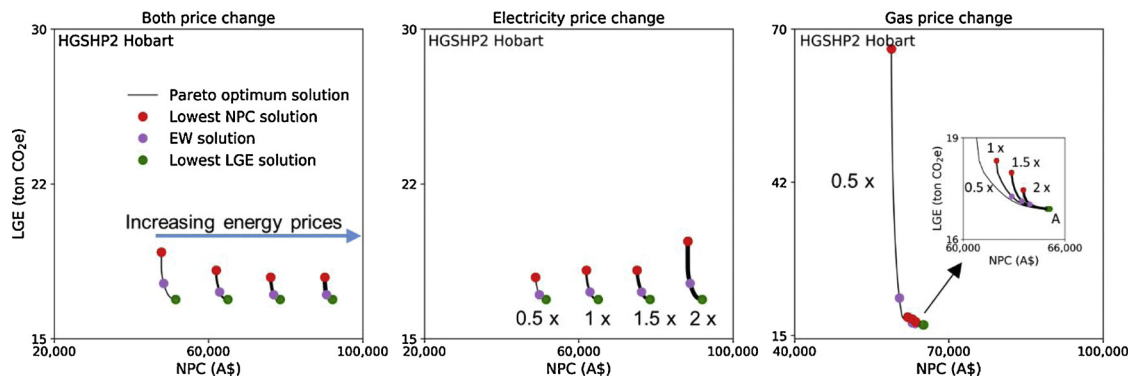


Fig. 10. Pareto optimum solutions for HGSHP2 systems in Hobart when energy prices change together and individually.

impact in the Pareto optimum solution range in HGSHP2 system compared to in HGSHP1 system. The lowest LGE solution is effectively the GSHP system, sized to provide 84 % of the peak load but able to meet 99 % of the annual thermal demand. The heating shave factor corresponding to the lowest NPC solution changes from 60 % to 66 % when both of the energy prices are changed from half of the current price to double the current price.

A gas furnace becomes more attractive when only the price of electricity is increased while keeping the gas price the same. This results in a slight increase in the range of Pareto optimum solutions as shown in Fig. 10. The lowest LGE solution is the same as before, which is with a GSHP system sized to meet 84 % of the peak load. The lowest NPC solution requires different heating shave factor depending on the price of electricity considered. When the price of electricity is doubled, the HGSHP2 system needs to have its GSHP unit sized to meet 58 % of the peak heating load, but still able to meet 95 % of the annual thermal demand.

Similarly, a gas furnace becomes more financially attractive when the gas price is decreased. The gas price becomes so low that heating by a gas furnace is much desired. At this point, the lowest TNC solution occurs when the GSHP system is sized at 10 % of the peak heating load. With this configuration, the GSHP system provides 30 % of the annual thermal demand while the gas furnace provides 70 %. However, this high gas consumption yields a significantly higher LGE (66 ton CO₂e). The lowest LGE solution remains the same where the GSHP unit sized to meet 84 % of the peak heating load. This is indicated as point A in Fig. 10. Since this point is effectively a GSHP system and only uses electricity, then point A represents all of this lowest LGE solution at any gas price.

3.5. Impact of changes in CoPs of RCAC and GSHP systems

The CoP of the RCAC and GSHP system influence how much electricity is consumed, which in turn determine the annual operating costs and emissions. The CoP values used in the above analysis was based on a specific heat pump unit with its relevant performance curve specified by the manufacturer. In this section, this CoP performance curve is adjusted by ± 0.5 to reflect a possible higher or lower efficient heat pump. Hence, on average, the CoP for an RCAC system in Sydney is around 2.6 ± 0.5 and the CoP for a GSHP system is 4.7 ± 0.5 . For simplicity, the efficiency of a gas furnace is kept the same (0.9) as this value represents the combustion rate of gas.

Fig. 11 presents the effect when the RCAC's CoP is adjusted. The changes in RCAC's CoP mostly affect the HGSHP1 system as it is purely a mix of GSHP and RCAC systems. As the CoP of RCAC decreases, the Pareto optimum solution range gets narrower in all three cities. The lowest LGE solutions slightly shift to the right indicating a slightly higher shave factor mix, but they are all effectively a hybrid system with the GSHP component providing 99 % of the annual thermal demand.

The lowest NPC solution has a higher NPC but a lower LGE when the RCAC's CoP is decreased. The GSHP system becomes more attractive as a less efficient RCAC unit is used. This results in a higher shave factor mix. Furthermore, utilising a more efficient GSHP system would reduce the lifetime emissions. In contrast, if a more efficient RCAC unit is used instead, the RCAC unit becomes the most cost-effective option. This is the case in Hobart and Cairns when the chosen RCAC unit has its CoP increased by 0.5.

The impact of changing the efficiency of the chosen GSHP unit is shown in Fig. 12. Using a less efficient GSHP unit shifts the Pareto optimum solution to the top right corner for both HGSHP1 and HGSHP2 system. Lower efficiency means more electricity consumption, which further increases NPCs and LGEs. Furthermore, lowering GSHP's CoP also makes a conventional system to be more attractive and this is indicated by the slight increase in the range of the Pareto optimum curve.

Similar to the above, HGSHP1 system is more sensitive to this efficiency changes as it represents a direct financial trade-off between GSHP and RCAC system. In this case, the lowest NPC solution gets closer to the conventional system as GSHP's efficiency decreases. In fact, the RCAC system is the lowest NPC solution in Hobart if a lower efficiency GSHP unit is used here.

Changing the efficiency of GSHP system has minimum impact on the hybrid shave factor mix for HGSHP2 systems in Sydney and Hobart. The reason behind this is a GSHP system is far more efficient compared to a gas furnace and the electricity to gas price ratio is relatively low in Australia. GSHP system is still preferred even when the CoP of the GSHP system is reduced by 0.5. However, if the GSHP CoP were reduced further and/or if the electricity and gas price ratio were to increase, then a conventional system may be preferred.

3.6. Impact of changes in emission factors

Sydney and Cairns have relatively high electricity emission factors due to the high proportion of fossil fuel used in the electricity generation fuel mix. This electricity emission factor is expected to decrease over time as more renewable energy is used as part of the fuel mix. In this section, the potential for 25 %, 50 % and 75 % reduction in this electricity emission factor is considered for the cases in Sydney and Cairns. The electricity in Hobart is assumed to be unchanged since most of it is already generated from renewable hydro sources. Up to 75 % potential decrease in emission factor is considered in Sydney and Hobart to make these values closer to the one in Hobart. Furthermore, the gas emission factor is assumed unchanged because this depends on the combustion rate of gas.

In Fig. 13, the Pareto optimum curve shifts downward as the electricity emission factor decreases, which represents lower lifetime emissions for all scenarios. Despite these drastic changes in the emission factor, there is minimal effect in the Pareto optimum solution curve. The lowest NPC solutions in each case refer to the same heating and cooling shave factors. They have the same NPCs but the LGEs value

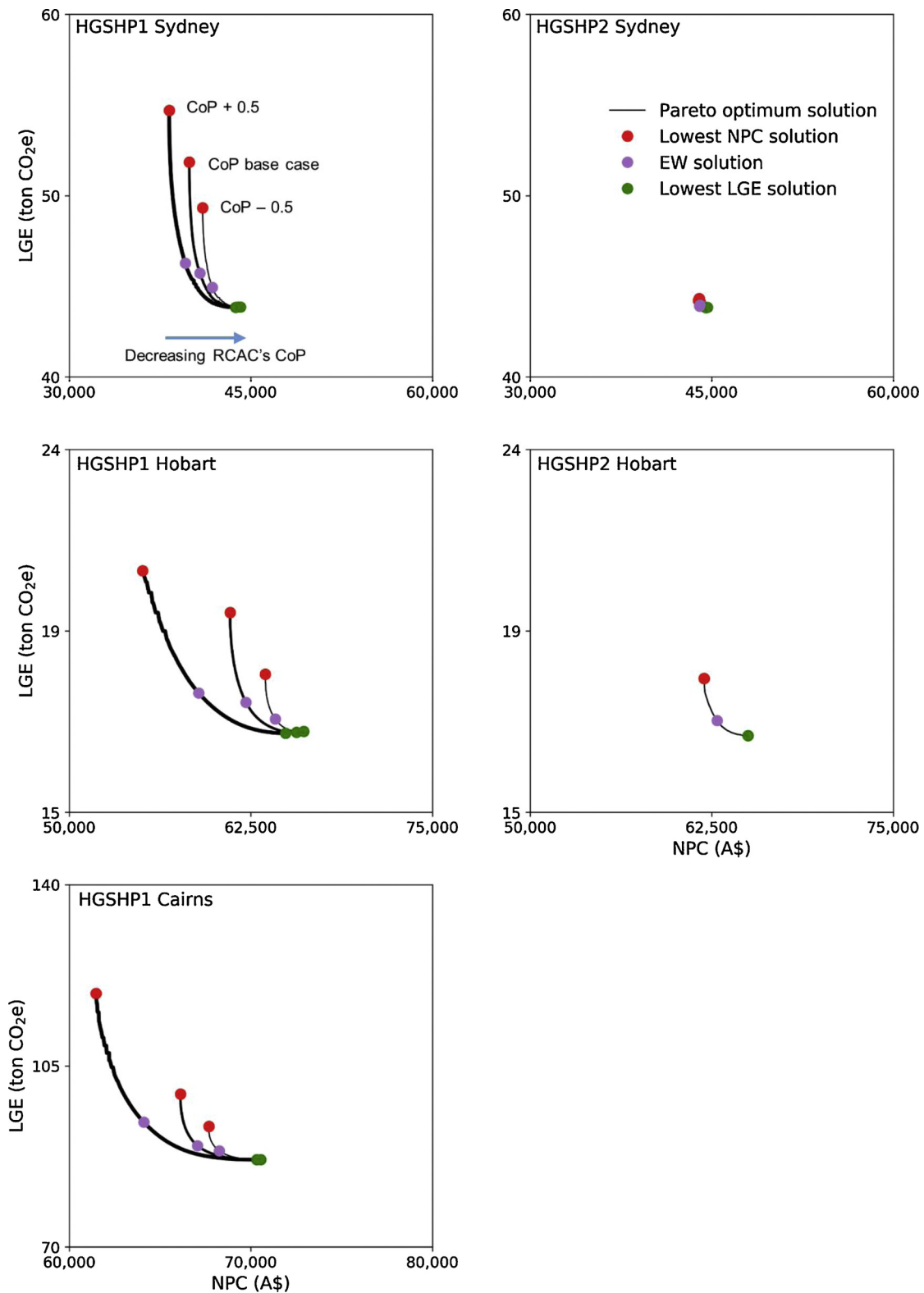


Fig. 11. Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney, Hobart and Cairns for RCAC's CoP of different CoPs.

decrease depending on the electricity emission factor.

The lowest LGE solutions follow a different pattern for HGSH1 and HGSH2 system when this emission factor is decreased. HGSH1 system only requires electricity to run. A lower electricity emission factor resulting in a lower lifetime emission. This means that the initial emission from GSHP system installation (including drilling for GHEs) becomes a larger and more significant component of the lifetime

emission. This encourages the hybrid system to adopt a lower proportion of the GSHP system component with a lower GHE length requirement. This is represented by the Pareto optimum curve gets slightly narrower in Fig. 13, where more conventional system usage is preferred.

In contrast, when gas is available as a substitute, a lower electricity emission factor increases the attractiveness for providing heating and

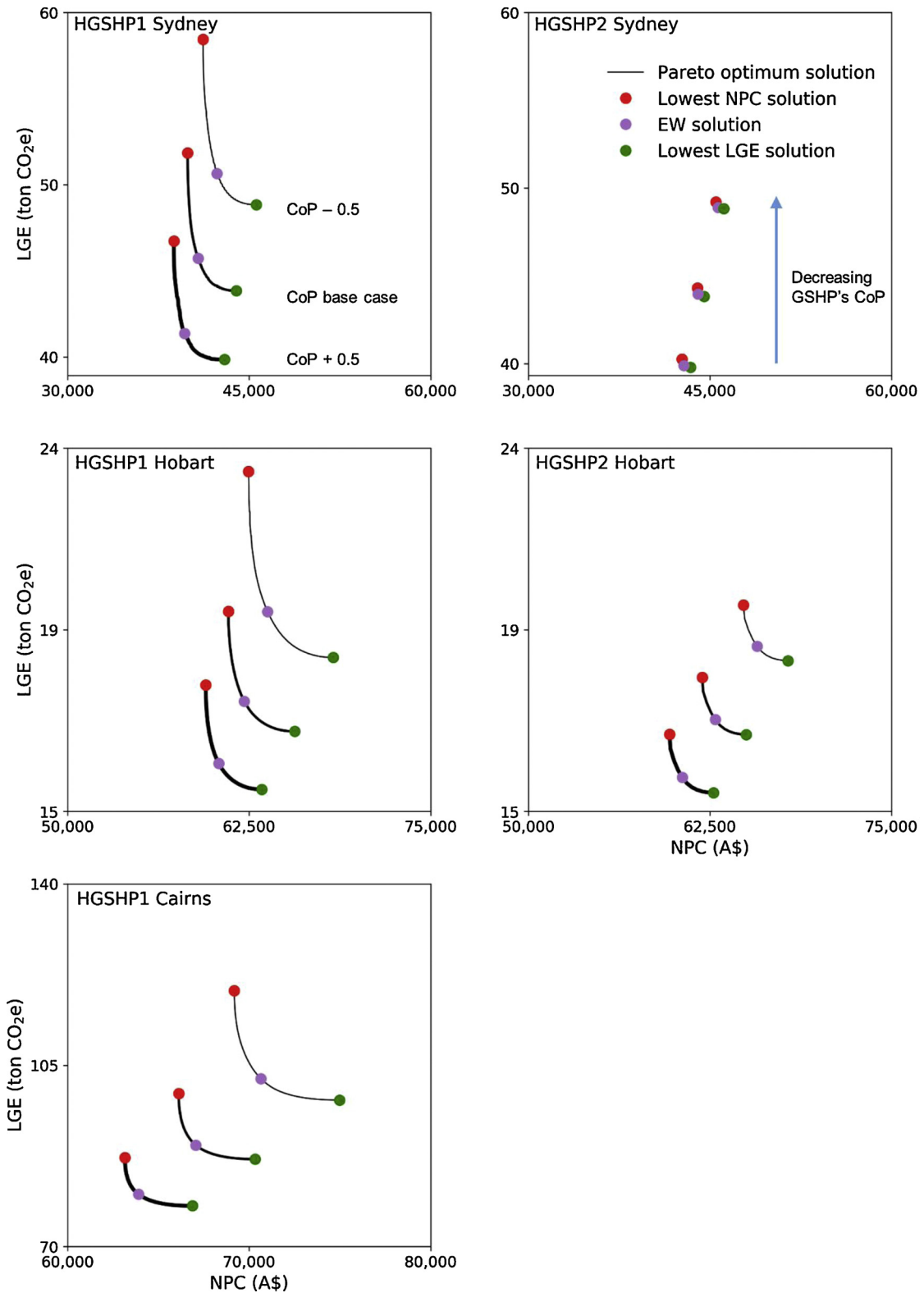


Fig. 12. Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney, Hobart and Cairns for GSHP's of different CoPs.

cooling by using a GSHP system. Initially, using electricity generates more than four times the emission than using gas, but the total annual GHG emission is still lower when using a GSHP system powered by electricity due to its higher efficiency. In the lower emission scenario, not only that GSHP system is more efficient, but electricity and gas emit similar amount of emissions. Hence, a GSHP system is much more preferred. This can be observed in Fig. 13 where the Pareto optimum

curve gets slightly longer for the HGSH2 system in Sydney when the electricity emission factor reduces.

4. Conclusion

In this paper, a multi-objective optimisation method is adopted where the economic and environmental performance of hybrid ground

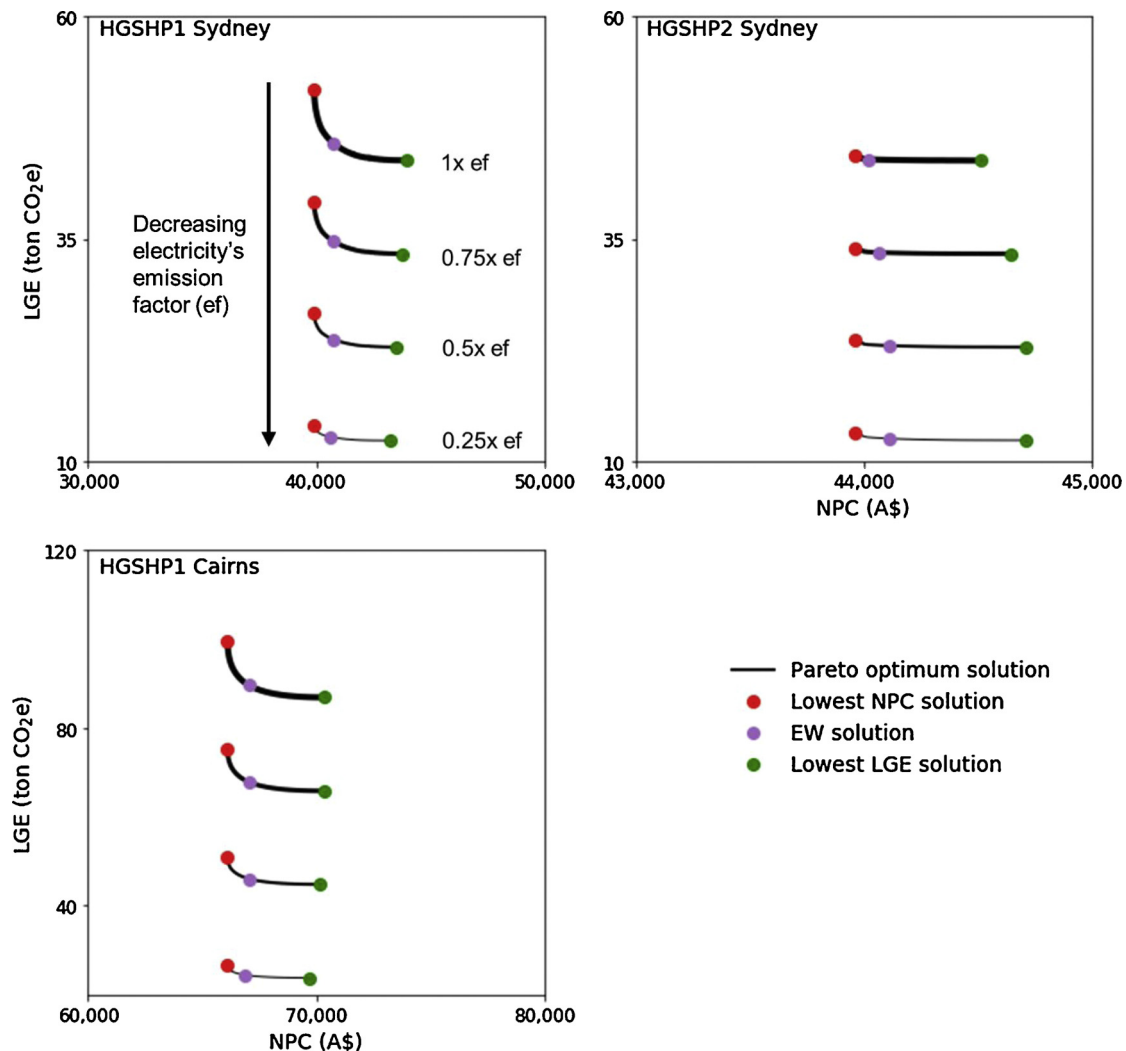


Fig. 13. Pareto optimum solutions for HGSH1 and HGSH2 systems in Sydney and Cairns when the electricity emission factor decreases.

source heat pump (HGSH1) systems in seven Australian cities are investigated. Two hybrid systems are considered. The first is a combination of a ground source heat pump (GSHP) system and a reverse cycle air conditioner (RCAC) system, and the second is a combination of a gas furnace, an RCAC for cooling and a GSHP system. A Pareto optimal approach is utilised to find the optimum solution set that considers both financial and environmental benefits of HGSH1 systems.

The results suggest that the hybrid system combination with the lowest lifetime costs is often different than the one with the lowest lifetime emissions. It turns out that they are affected by the climatic conditions, efficiency of the systems, energy price ratio between electricity and gas and the emission factor ratio between electricity and gas.

The second part of this paper considers the impact when any of these variables change. Changes such as an increase in energy price or an increase in the efficiency of the GSHP system or a decrease in the emission factor ratio typically result in the GSHP system being preferred. This is often indicated by the Pareto optimum solution range getting narrower and the lowest cost and emission solution converging as the GSHP system. On the contrary, changes such as an increase in drilling costs or an increase in the efficiency of the conventional system cause a higher proportion of conventional systems to be preferred. A conventional system can be preferred in some extreme cases. One example is when the cost to install the ground heat exchanger component for the GSHP systems becomes too expensive because the system is installed in a heating-dominant climate such as Hobart and in a location

with very poor ground thermal conductivity. When a conventional system is preferred, the Pareto optimum solution range is relatively wide and the lowest cost and emission solutions can differ significantly.

Overall, the results presented here allow homeowners to make informed decisions for choosing their heating and cooling systems based on climatic, location, cost and emission conditions. Depending on the desired objective, one has the choice to minimise their lifetime costs or emissions. A solution which considers both the lifetime costs and emissions with equal weight was also provided.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the

online version, at doi:<https://doi.org/10.1016/j.geothermics.2020.101868>.

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Appendix B

Complementary data from Chapter 3 and 4:

**Detailed instrumentation and summary for each property in
the SEPD project**

Sustainable Energy Pilot Demonstration Project

In the last few years, concerns about climate change have driven an increase in renewable technology research and development to reduce carbon emissions. One such development is in ground source heat pump (GSHP) system to provide efficient heating and cooling to buildings using sustainable energy from the ground.

23 GSHP systems were installed throughout metropolitan Melbourne as part of the Sustainable Energy Pilot Demonstration (SEPD) project. The location of the monitored properties is shown below. This attachment presents a summary for each of these monitored properties along with some performance data whenever available.

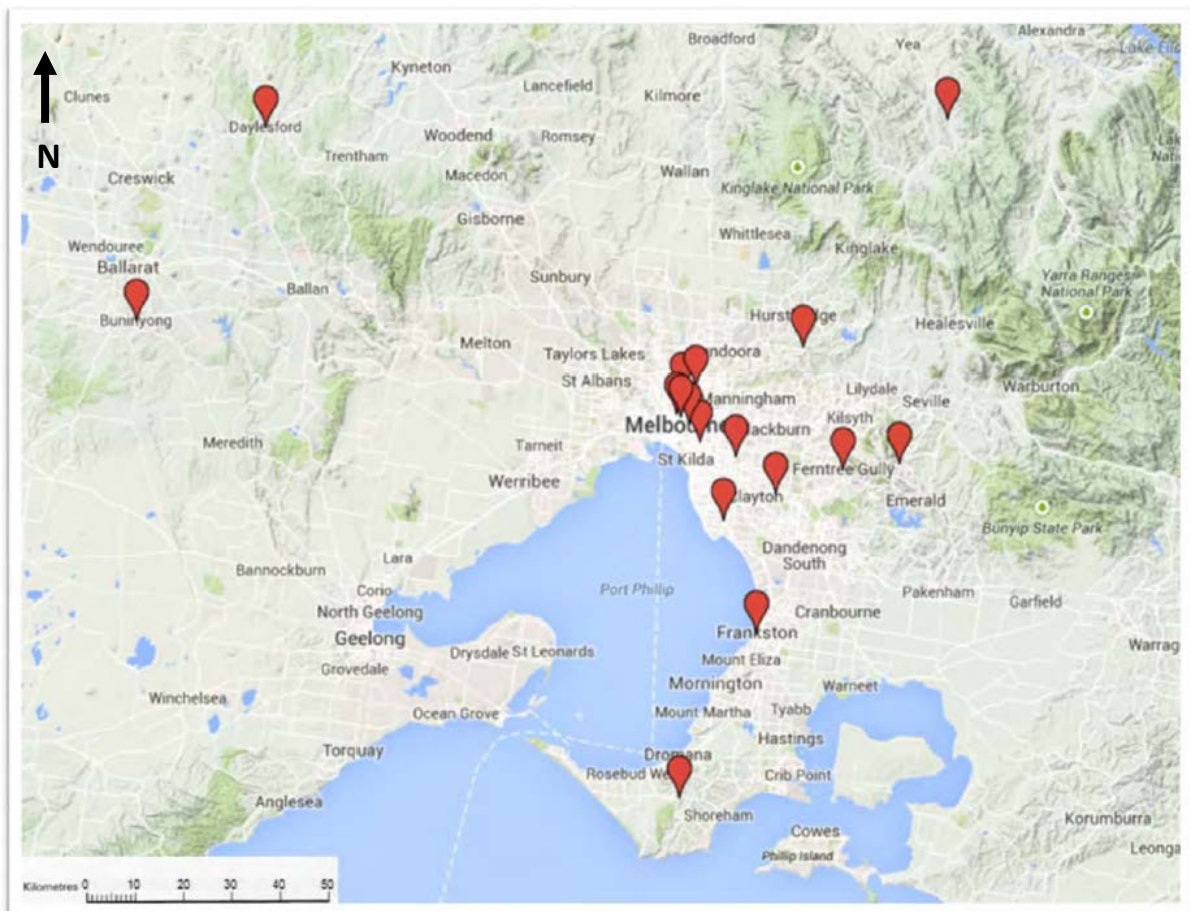


Figure B-1: Location of the monitored properties

Ashburton

Ground components: 4 ground heat exchangers, 90 m depth with single U-loop in each borehole

Heat pump size: 32 kW

Distribution system: Floor hydronic heating, fan coil unit for cooling, water & pool heating

Status: Completed in June 2015

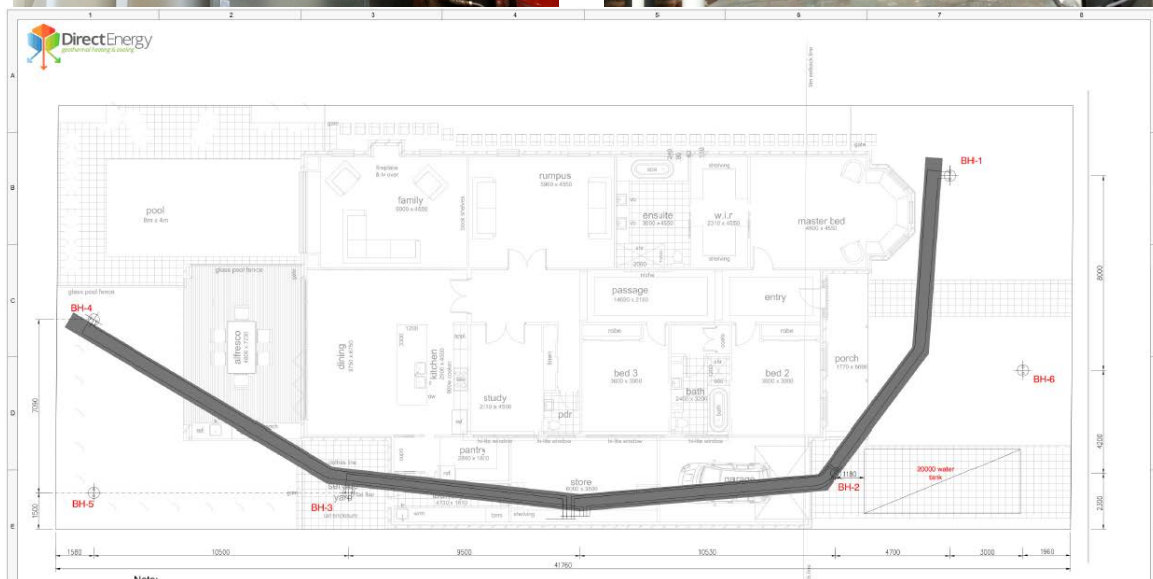


Figure B-2: (top row) installation of ground heat exchangers, (middle row) plant room and (bottom row) schematic of ground heat exchangers location at Ashburton

Instrumentation

- 14 temperature sensors were installed in 2 ground heat exchangers as outlined below.
- 2 flow meters to measure the flow of water into the ground and into the building.
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- Power meter measures power consumption

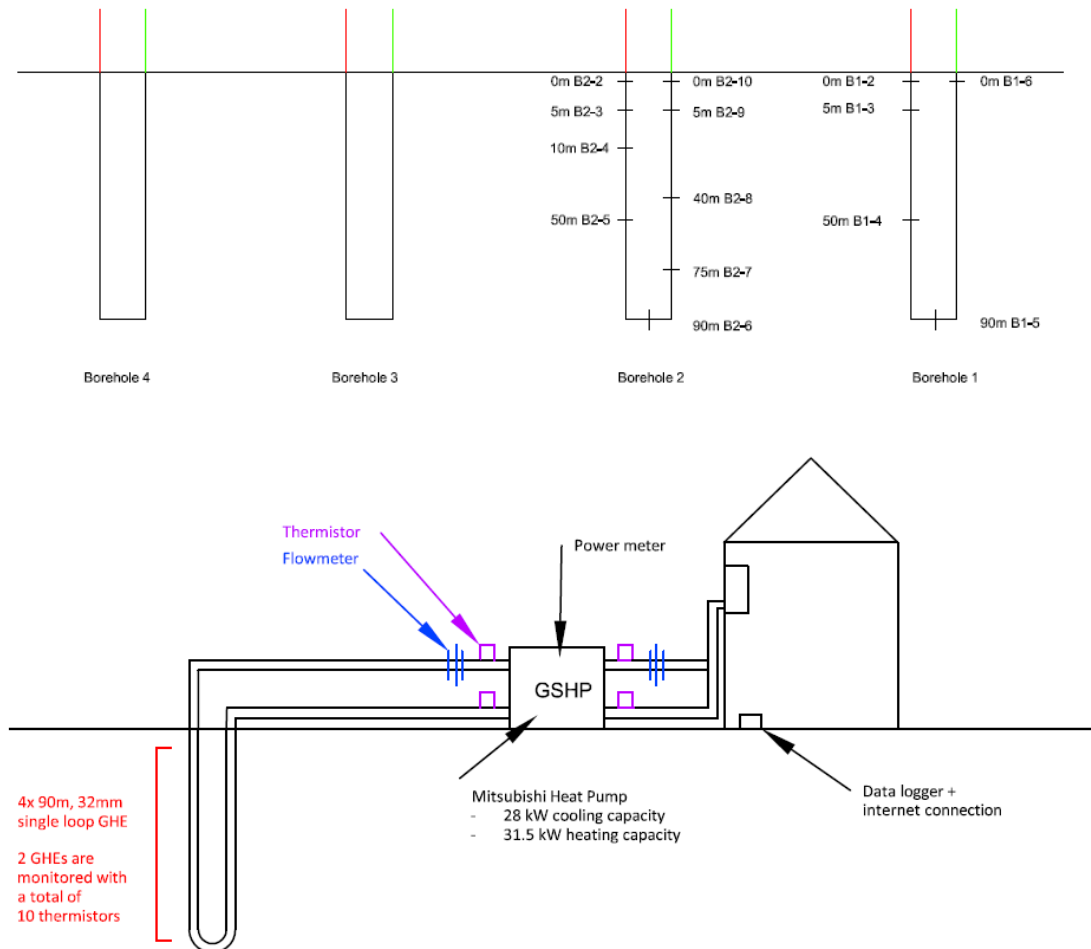


Figure B-3: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-1: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Ashburton

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Jun – Dec 2015	1,138	371	34	17,794	2,276	5,277	3.8
Jan – Dec 2016	2,631	1,286	45	48,378	6,838	14,840	3.7
Jan – Dec 2017	755	1,059	45	13,638	6,005	5,535	3.5
Jan – Aug 2018	813	1,321	36	13,503	6,877	6,098	3.3

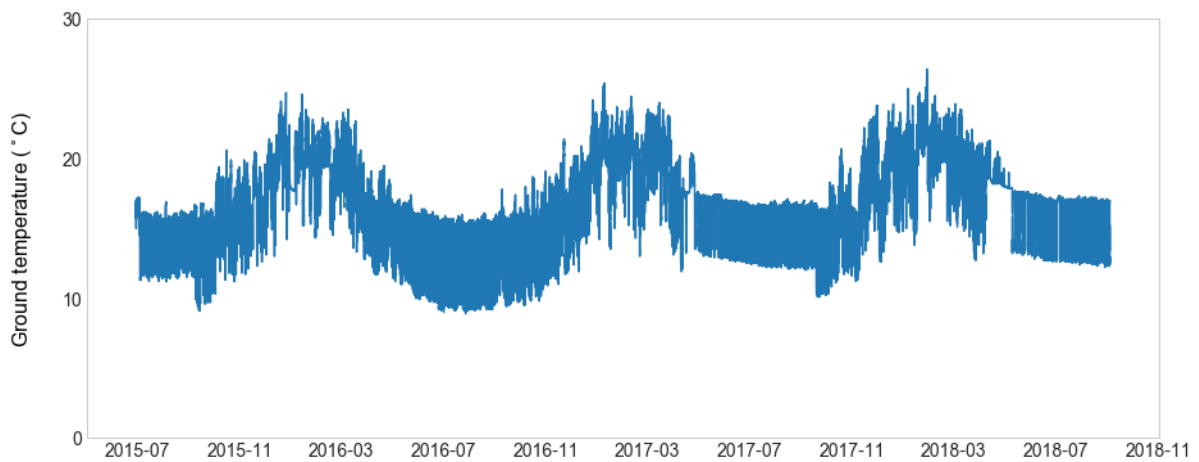


Figure B-4: Ground temperature monitored at borehole 1 (90 m depth)

Buninyong

Ground components: ground heat exchangers are installed in 4 trenches, 40 m long. Each trench contains 4 circuits at different depth.

Heat pump size: 8 kW

Distribution system: fan coil unit for heating and cooling

Status: Completed in November 2016



Figure B-5: (top row) installation of ground heat exchangers, (middle row) installation of thermal response test pit and instrumentation, and (bottom row) set up of heat pumps and data logger

Instrumentation

- 3 sensors were installed at 1.5m depth and 3 sensors at 2.5 m depth at trench no 2
- Far-field temperature sensor at 2.5m depth to monitor the ground temperature.
- A sensor at 2.5m depth was installed between trench 2 and 3 to monitor the heat influence on the ground.
- 2 sensors in PT ports were installed to monitor flow and return to trench 1 and 3
- 8 sensors in PT ports were installed to monitor flow and return to trench 2
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

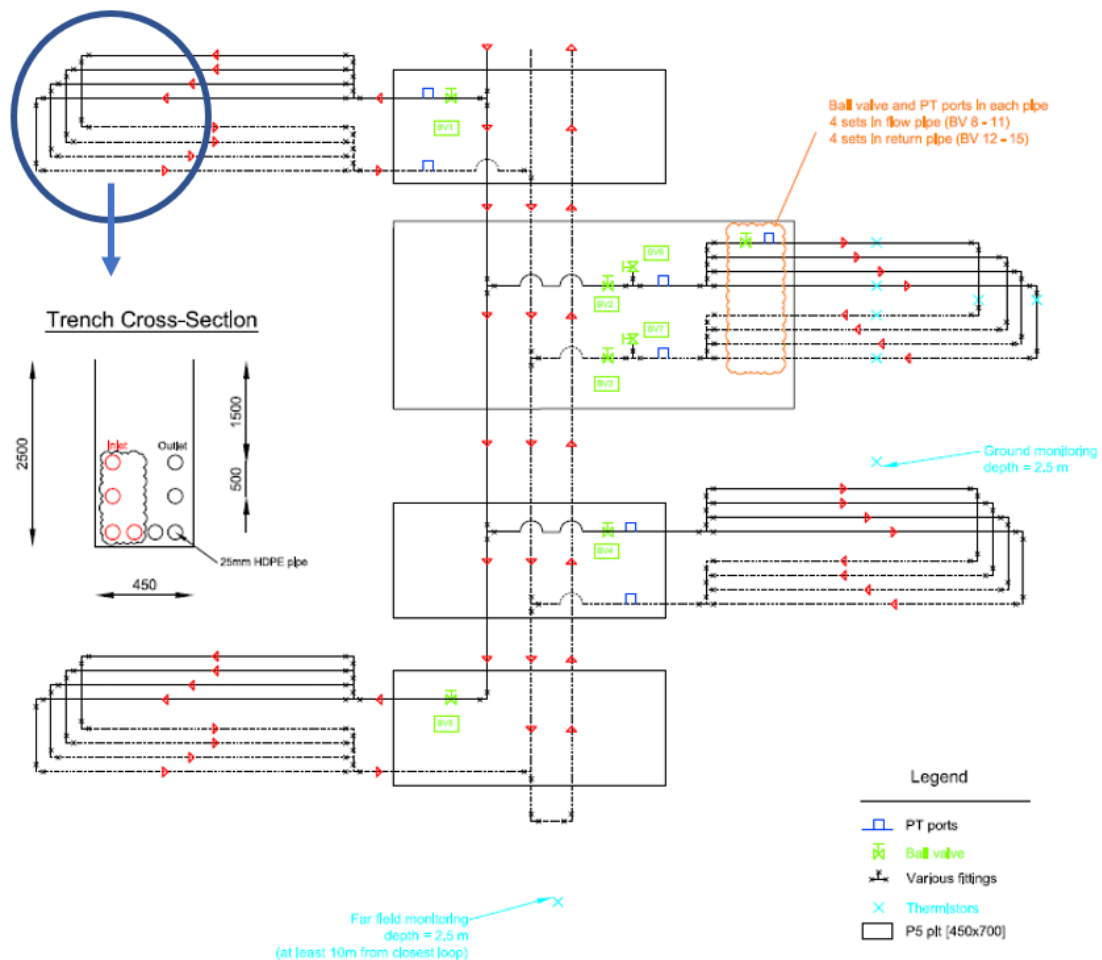


Figure B-6: Schematic of trench detail and instrumentation location

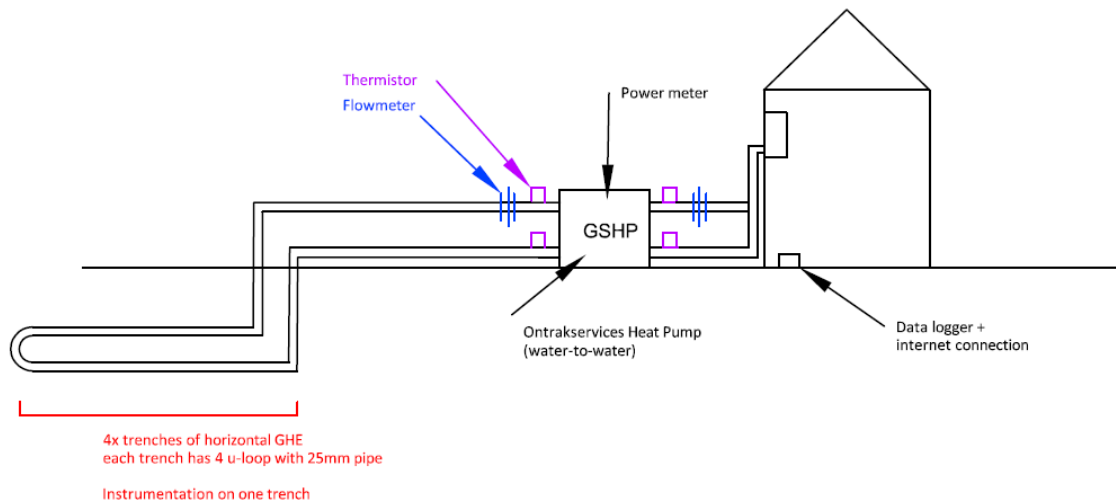


Figure B-7: instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-2: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Buninyong

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Nov – Dec 2016	46	0	3	382	0	111	3.4
Jan – Dec 2017	710	230	10	4,513	1,214	2,079	2.8
Jan 2018	1	58	8	5	281	140	2.0

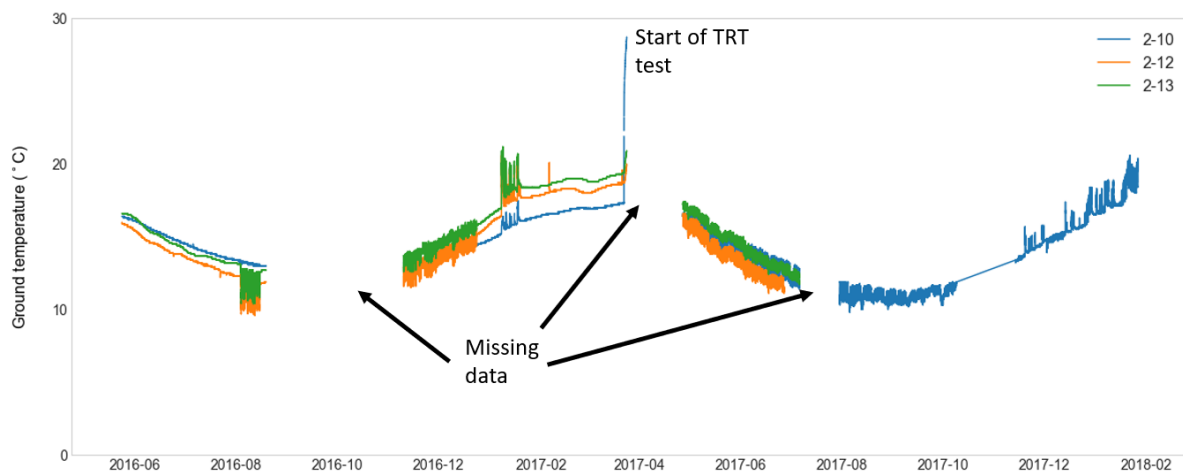


Figure B-8: Ground temperature monitored at trench no 2

Carlton

Ground components: 50 ground heat exchangers, 20 m depth with single U-loop in each borehole

Heat pump size: 330 kW in total. 9 GSHPs were installed

Distribution system: Ducted heating and cooling

Status: Installation was completed in mid-2015, but monitoring ended up was not performed



Figure B-9: Heat pumps installed inside the plant room

Cheltenham (residential)

Ground components: 2 ground heat exchangers, 55 m depth with single U-loop in each borehole

Heat pump size: 8.5 kW

Distribution system: Ducted heating and cooling

Status: Completed in August 2015

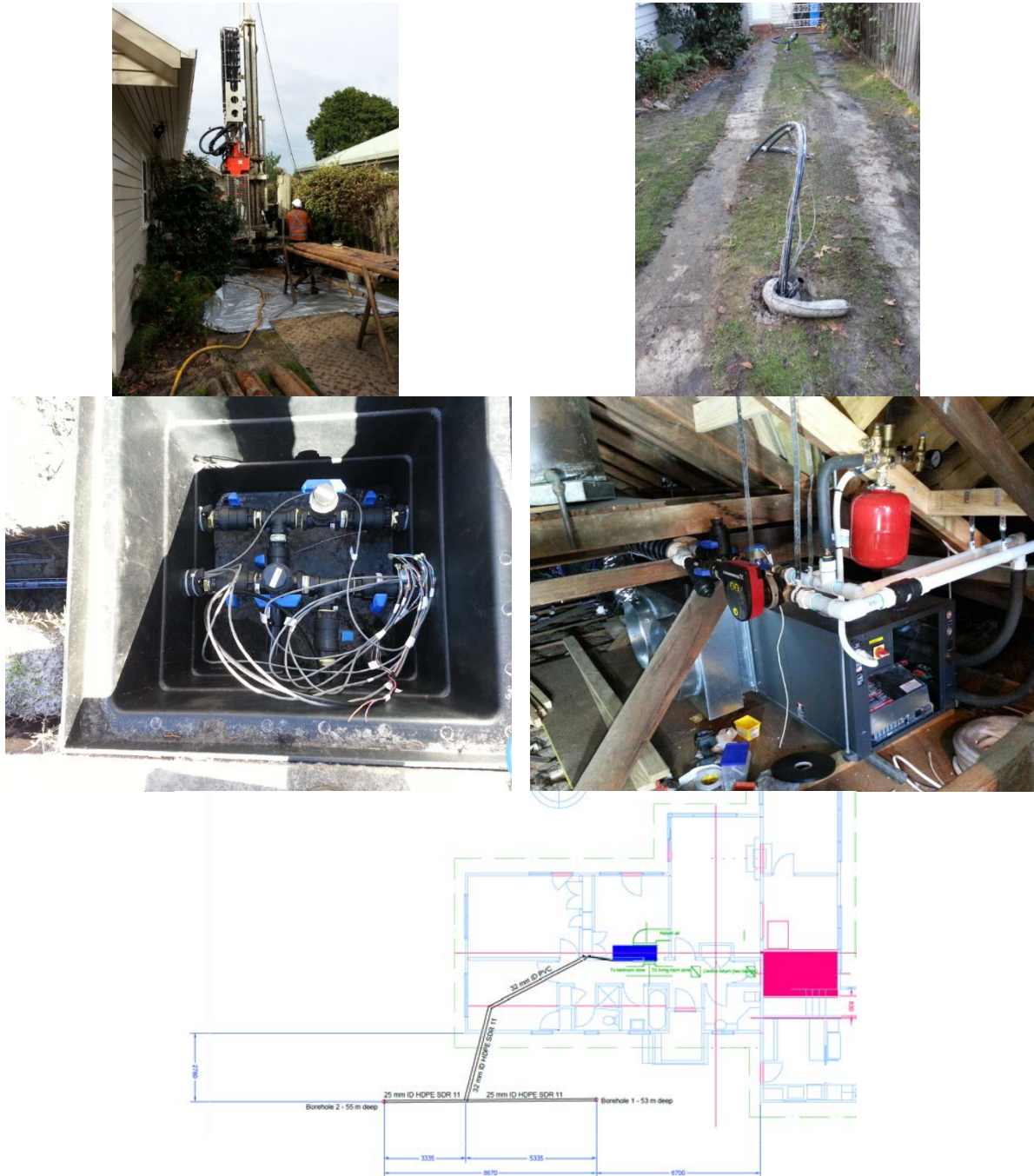


Figure B-10: (top row) installation of ground heat exchangers, (middle row) installation of thermal response test pit and heat pump in the roof cavity, and (bottom row) schematic of borehole location and header pipes

Instrumentation

- 8 Temperature sensors were installed around each ground heat exchangers
- 1 Temperature sensors were installed to measure the ground temperature at the depth where the header pipes were installed (600mm depth from the ground surface and 600mm depth away from GHE1).
- 1 Temperature sensors were installed to measure air temperature.
- 1 flow meter was installed to measure the flow of water into the ground.
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- Power meter measures power consumption

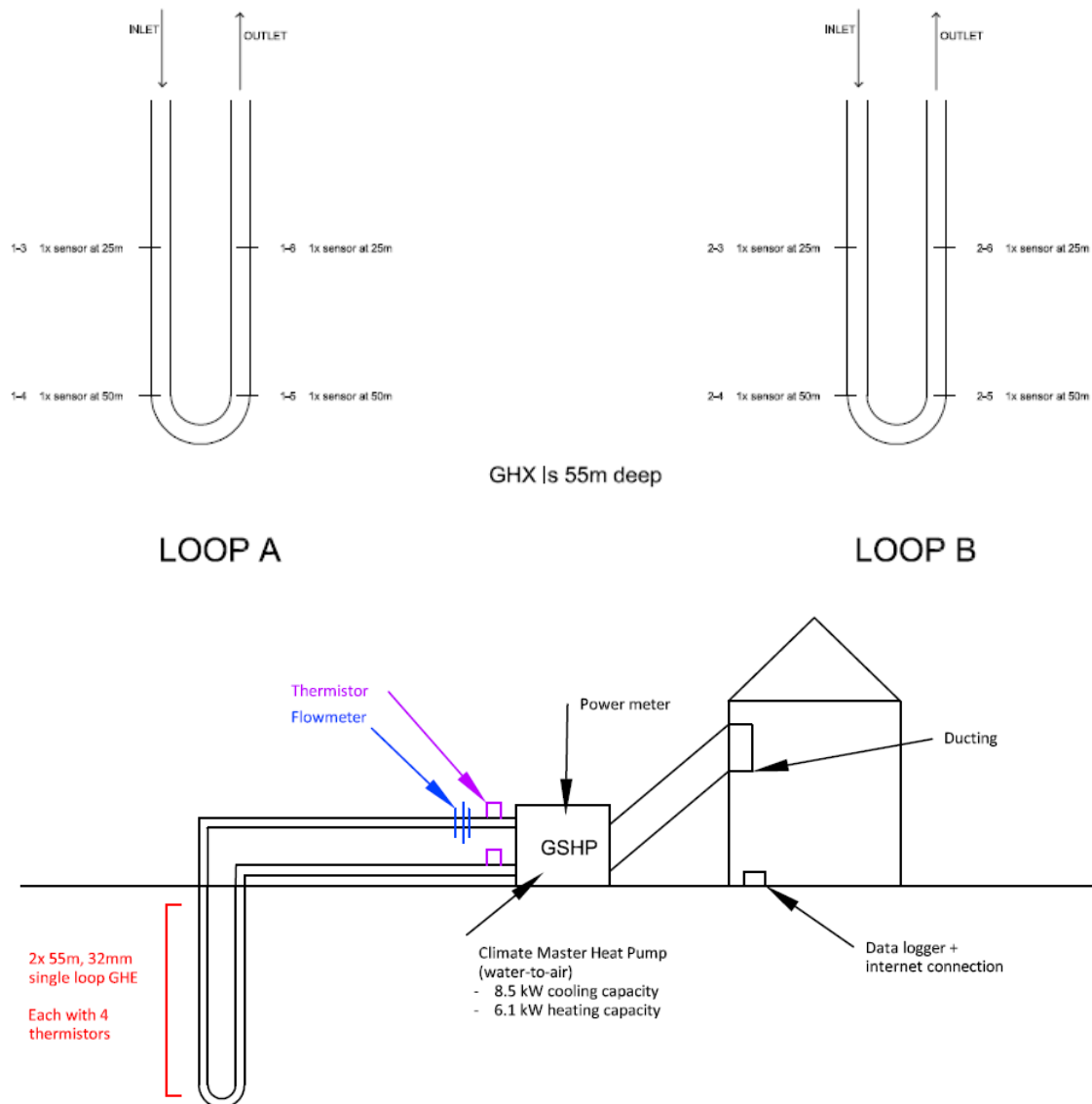


Figure B-11: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-3: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Cheltenham (residential)

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Aug – Dec 2015	183	32	6	1,110	208	327	4.0
Jan – Dec 2016	481	44	6	2,471	278	780	3.5
Jan – Dec 2017	522	64	7	2,627	409	863	3.5
Jan – Aug 2018	630	56	12	3,061	363	1,014	3.4

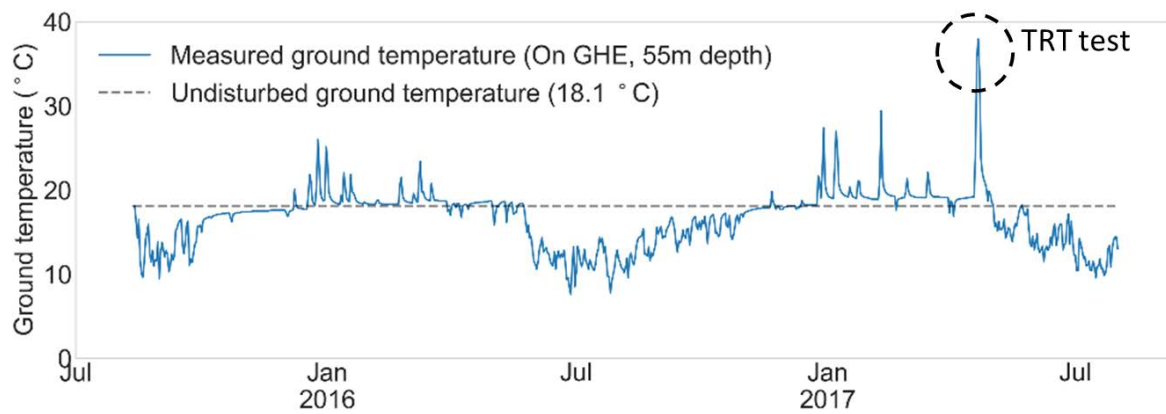


Figure B-12: Ground temperature monitored at borehole 1 (55 m depth)

Cheltenham (commercial)

Ground components: 2 ground heat exchangers, 60 m depth with single U-loop in each borehole

Heat pump size: 8.6 kW

Distribution system: Hydronic panel on the wall and ceiling fan coil unit

Status: Completed in May 2015. However, this property is an office of a plumber. Hence, the system is rarely used.



Figure B-13: (top row) installation of ground heat exchangers, and (bottom row) heat pump configuration and instrumentation used

Instrumentation

- 4 Temperature sensors were installed around each ground heat exchangers with the configuration as outlined below.
- 4 temperature sensors were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

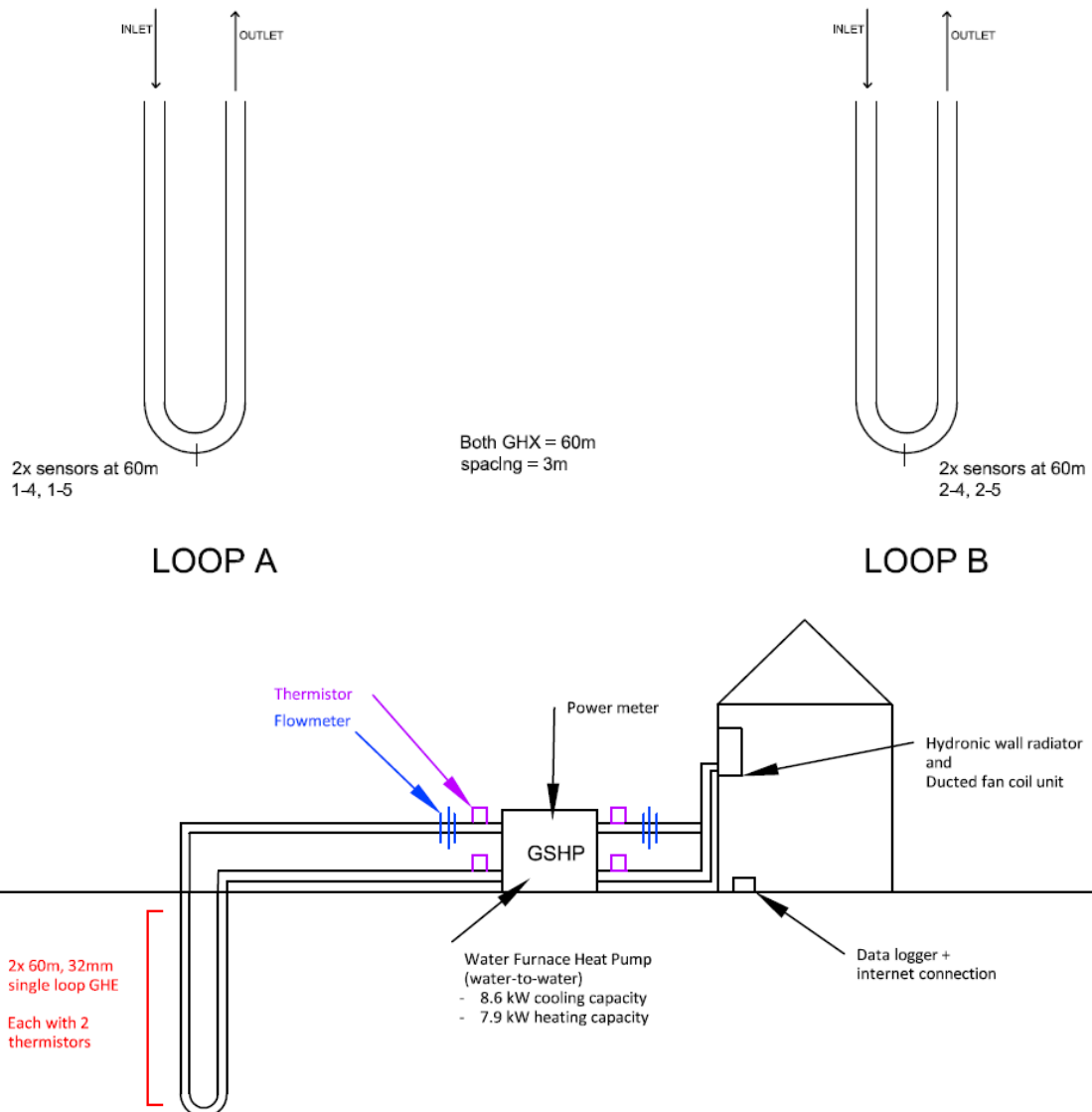


Figure B-14: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-4: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Cheltenham (commercial)

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
May – Dec 2015	32	21	1	218	65	104	2.7
Jan – Dec 2016	22	36	1	161	129	135	2.1
Jan – Apr 2017	0	8	-	3	37	20	2.0

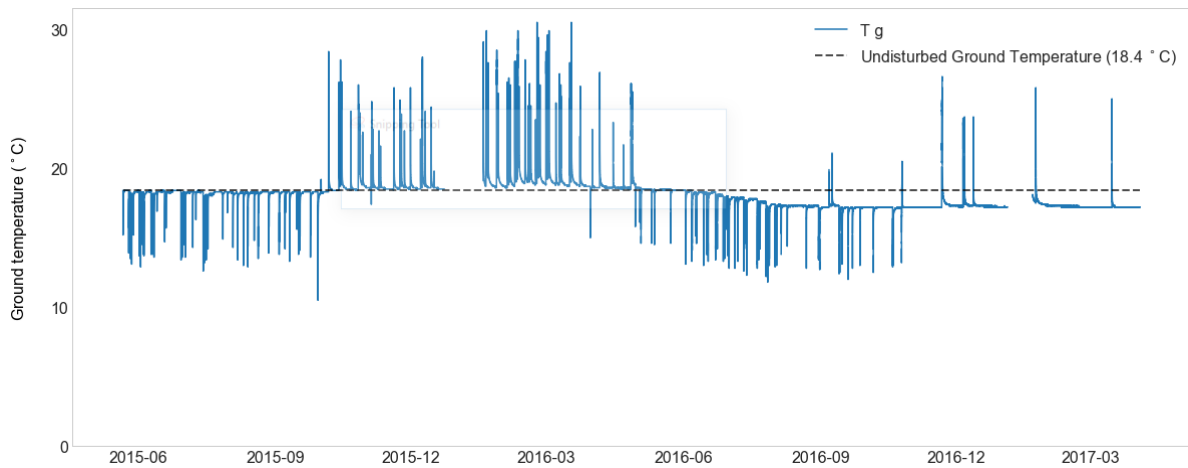


Figure B-15: Ground temperature monitored at borehole 1 (60 m depth)

Daylesford

Ground components: 3 ground heat exchangers, with 40 m, 55 m and 65 m depth

Heat pump size: 8 kW

Distribution system: Wall split systems for heating and cooling

Status: Installation was completed in 2016. But monitoring was not continued

Instrumentation

- 6 Temperature sensors were installed around each ground heat exchangers with the configuration as outlined below.

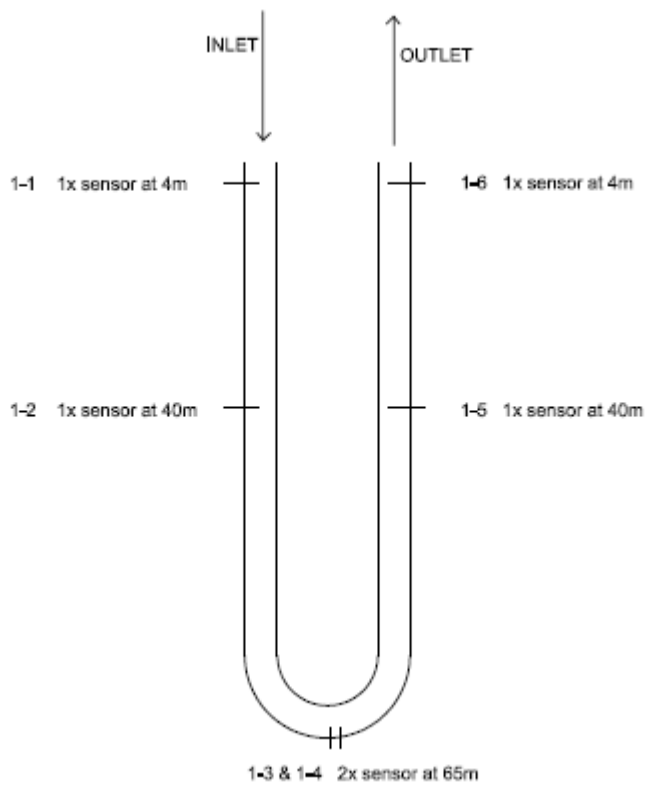


Figure B-16: Instrumentation schematic for the ground heat exchangers

East Brunswick

Ground components: 2 ground heat exchangers, 65 m depth with double U-loop in each borehole

Heat pump size: 8 kW

Distribution system: Hydronic panel on the wall and ceiling fan coil unit for cooling

Status: Completed in August 2015. However as this is a display house, the usage of the system is very limited. The installed heat pump is a locally made prototype and later replaced with a better-quality heat pump

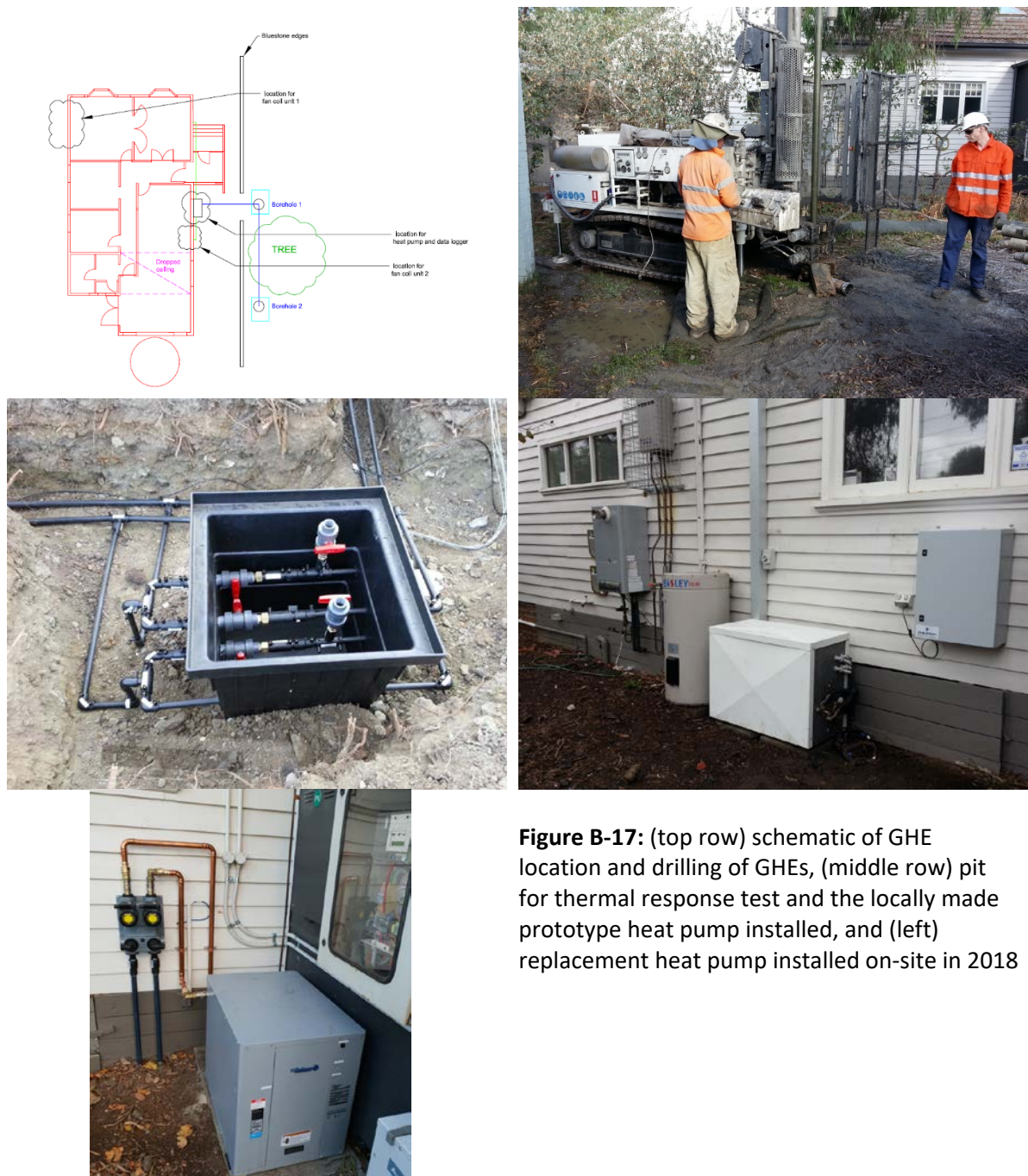


Figure B-17: (top row) schematic of GHE location and drilling of GHEs, (middle row) pit for thermal response test and the locally made prototype heat pump installed, and (left) replacement heat pump installed on-site in 2018

Instrumentation

- 8 Temperature sensors were installed in 2 ground heat exchangers as outlined below (2 of them are PT ports).
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

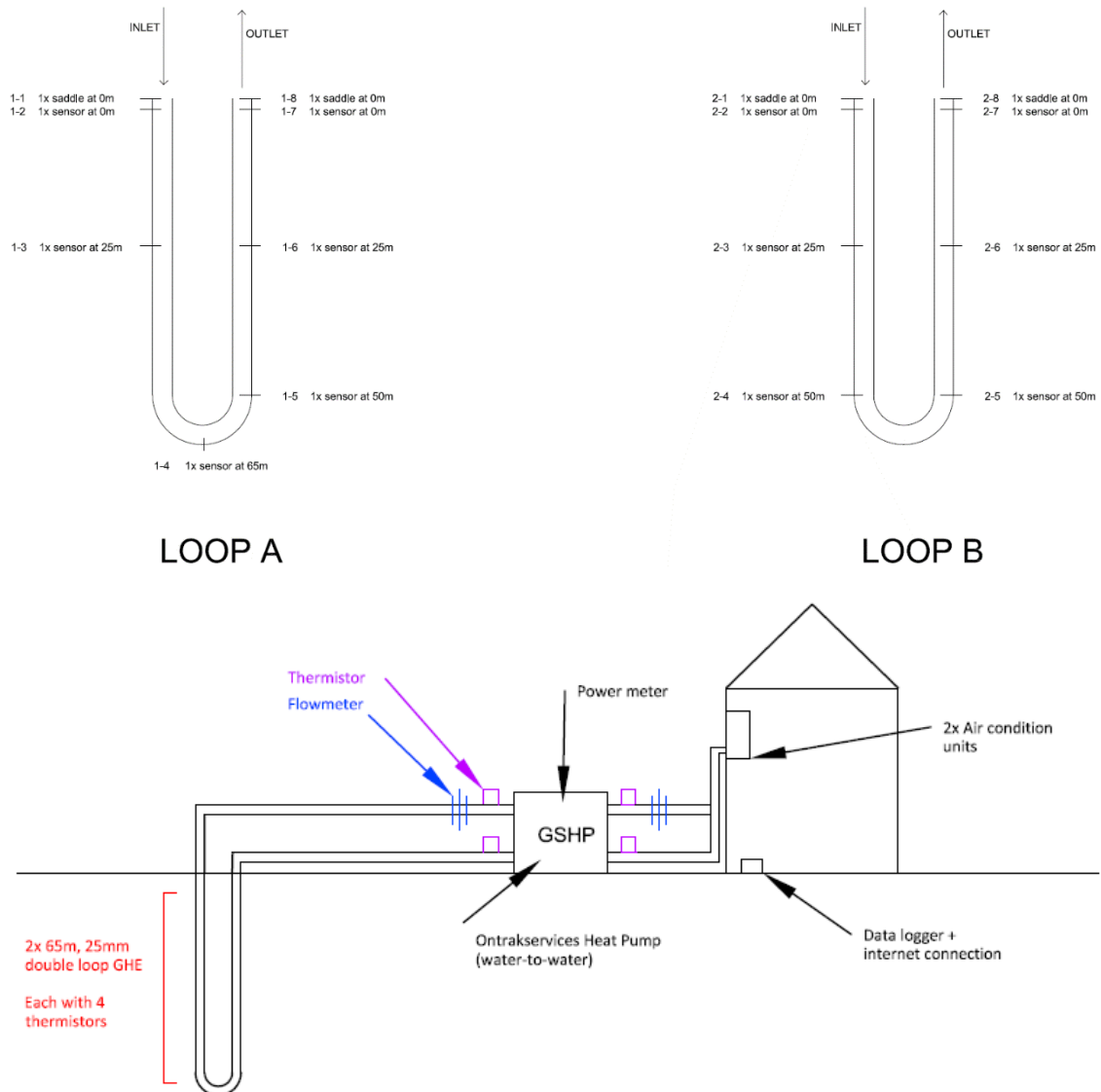


Figure B-18: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-5: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in East Brunswick

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Aug – Dec 2015	52	1	2	108	1	77	1.4
Jan – Jul 2016	125	0	3	430	0	217	2.0

Note: No usage observed after July 2016 due to GSHP malfunction. Hence, the data are not included here

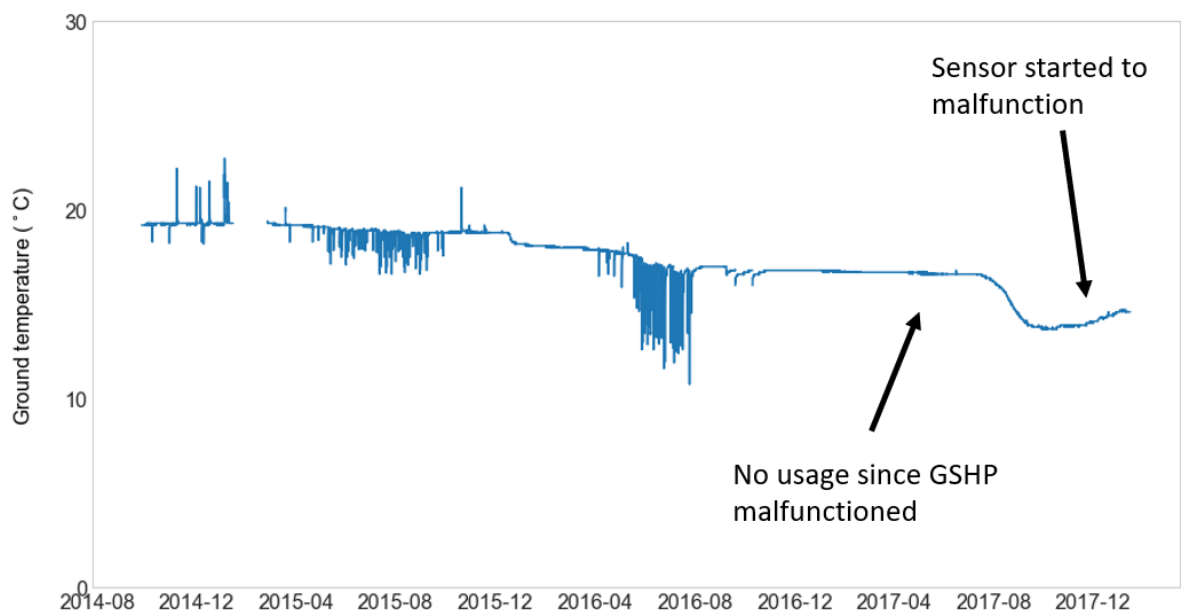


Figure B-19: Ground temperature monitored at borehole 1 (25 m depth)

East Melbourne

Ground components: 2 ground heat exchangers, 60 m depth with single U-loop in each borehole

Heat pump size: 11 kW

Distribution system: Ducted heating and cooling, domestic hot water and spa heating

Status: Completed in September 2015

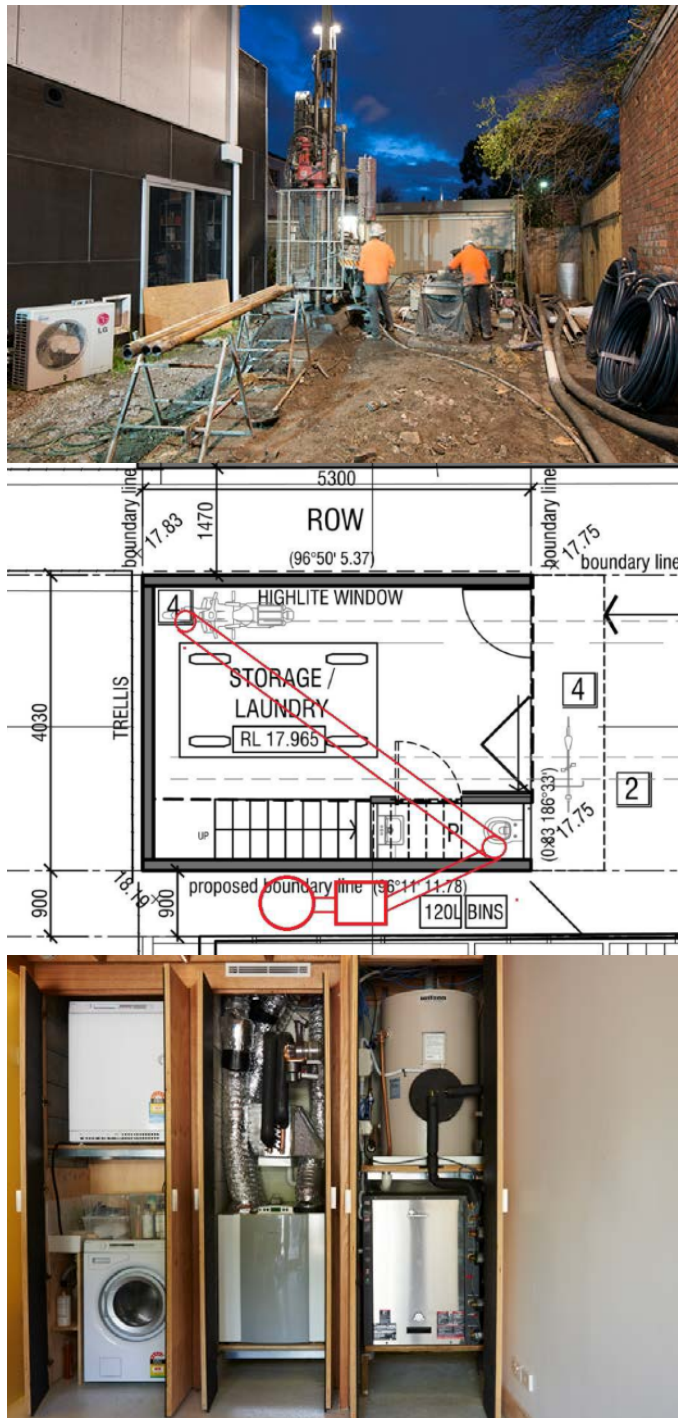


Figure B-20: (top row) installation of ground heat exchangers, (middle row) schematic of ground heat exchangers location, and (bottom row) heat pump and hot water tank

Instrumentation

- 12 Temperature sensors were installed in 2 ground heat exchangers as outlined below.
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

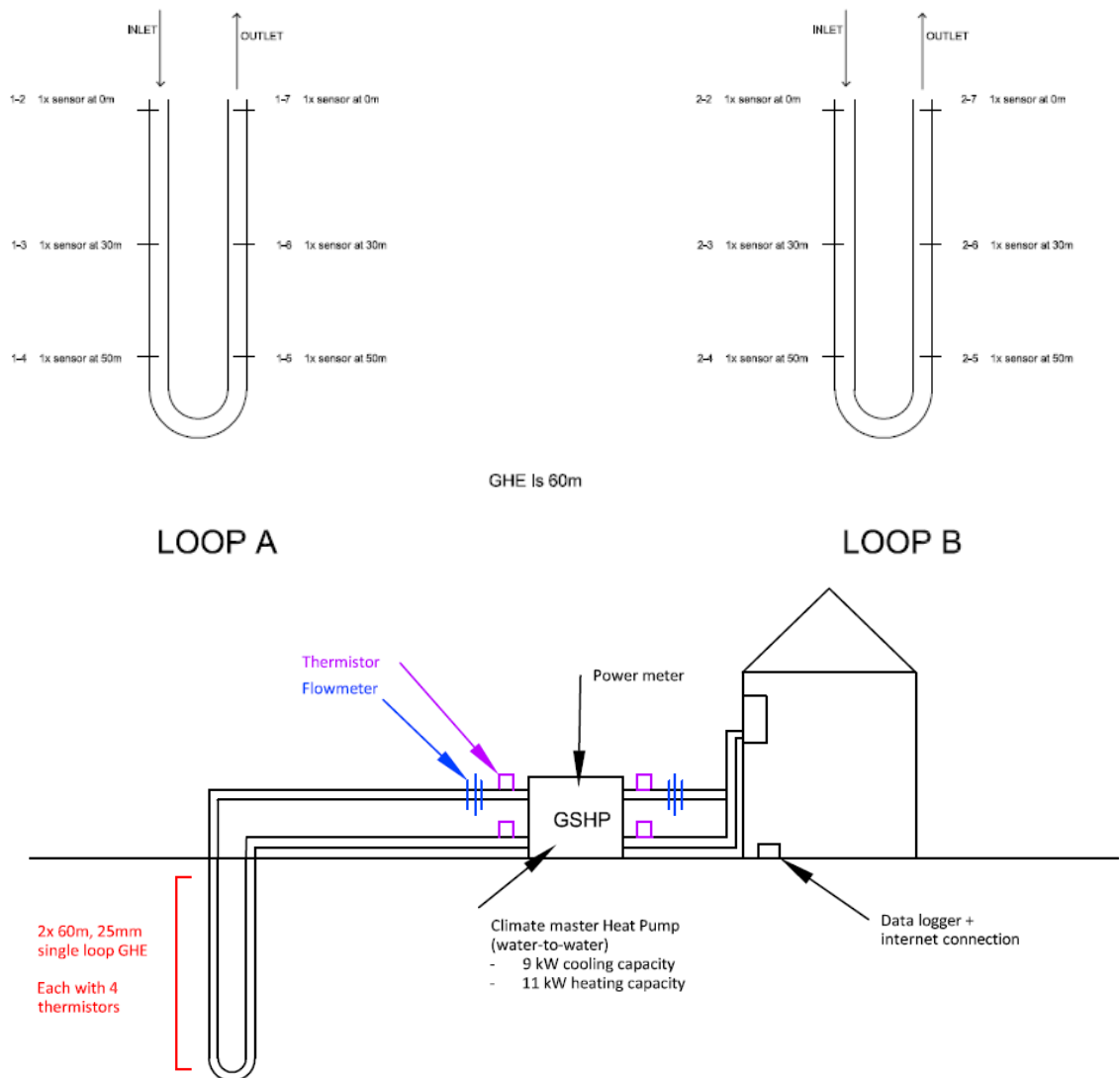


Figure B-21: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-6: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in East Melbourne

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Sep – Dec 2015	161	491	23	819	1,553	1,083	2.2
Jan – Dec 2016	686	439	13	4,059	1,435	1,869	2.9
Jan – Dec 2017	1,383	542	22	7,536	1,568	3,196	2.8
Jan – Apr 2018	101	251	12	512	827	583	2.3

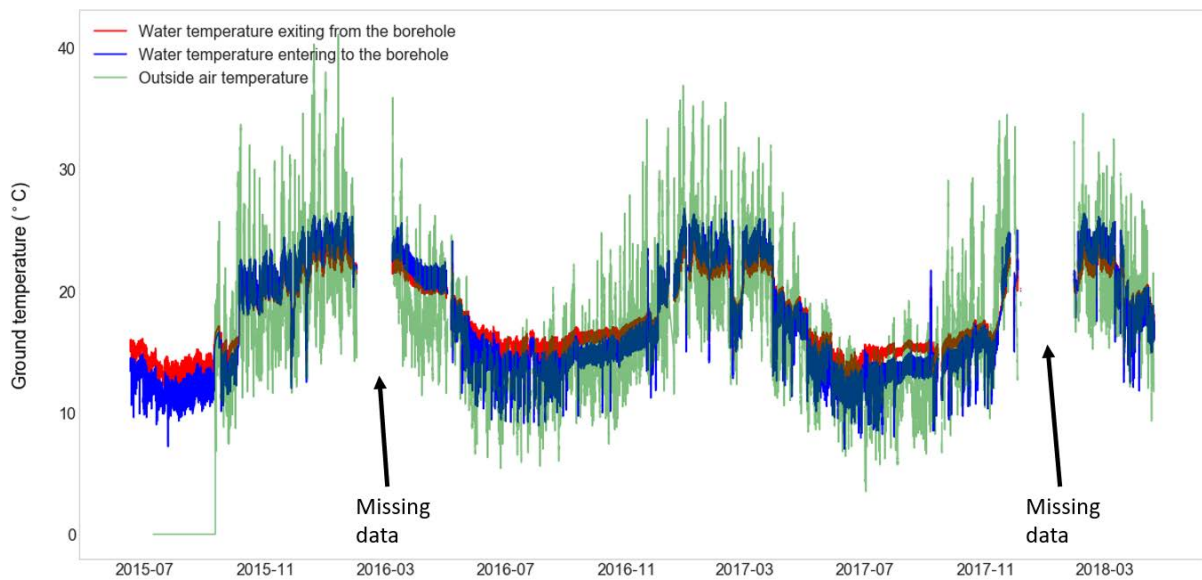


Figure B-22: Water temperature exiting and entering borehole form BH1

Ferntree Gully

Ground components: 3 ground heat exchangers, 55 m depth with single U-loop in each borehole

Heat pump size: 24 kW

Distribution system: Three wall split systems for heating and cooling and domestic hot water

Status: Completed in January 2014. However, due to data logger malfunction, most data collected prior to July 2015 was lost

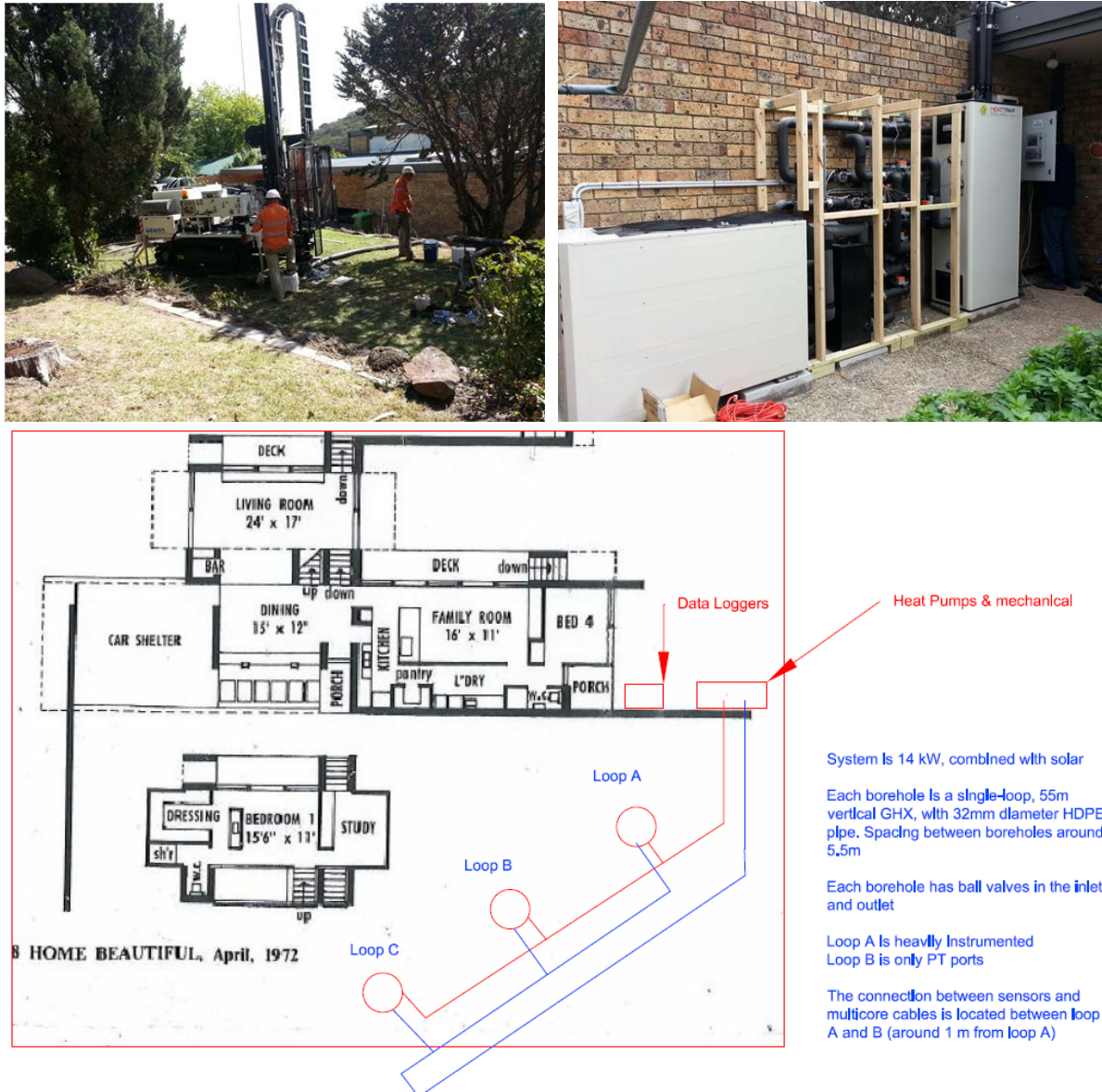


Figure B-23: (top row) installation of ground heat exchangers and set up of heat pump and hot water tank, and (bottom row) schematic of ground heat exchangers location and heat pump

Instrumentation

- 15 Temperature sensors were installed in 2 Ground heat exchangers as outlined below
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

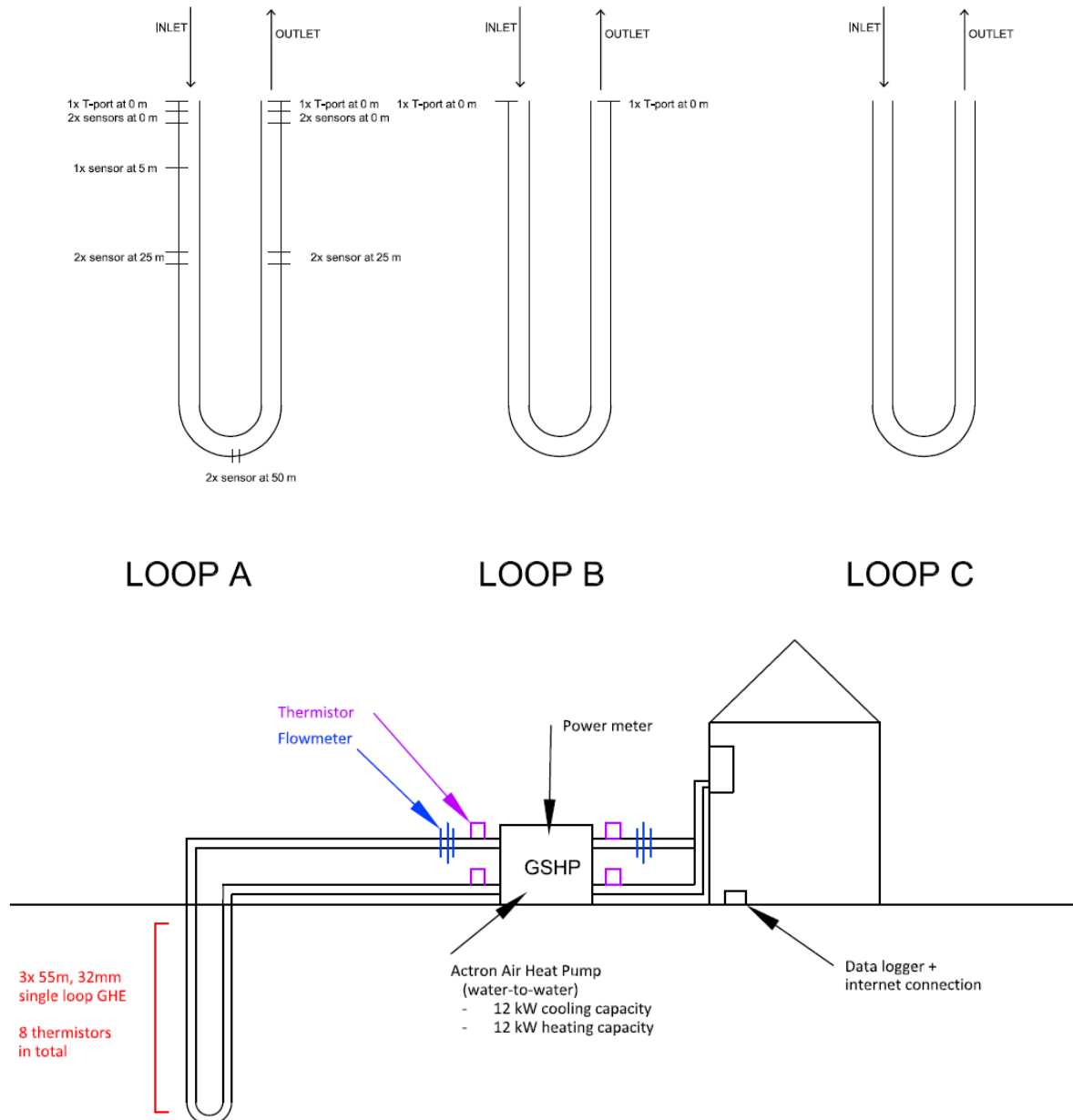


Figure B-24: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-7: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Ferntree Gully

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Jul – Dec 2015	686	130	19	3,986	1,975	1,989	3.0
Jan – Dec 2016	1,670	204	21	9,671	2,509	4,565	2.7
Jan – Dec 2017	1,579	125	20	9,786	1,337	4,151	2.7

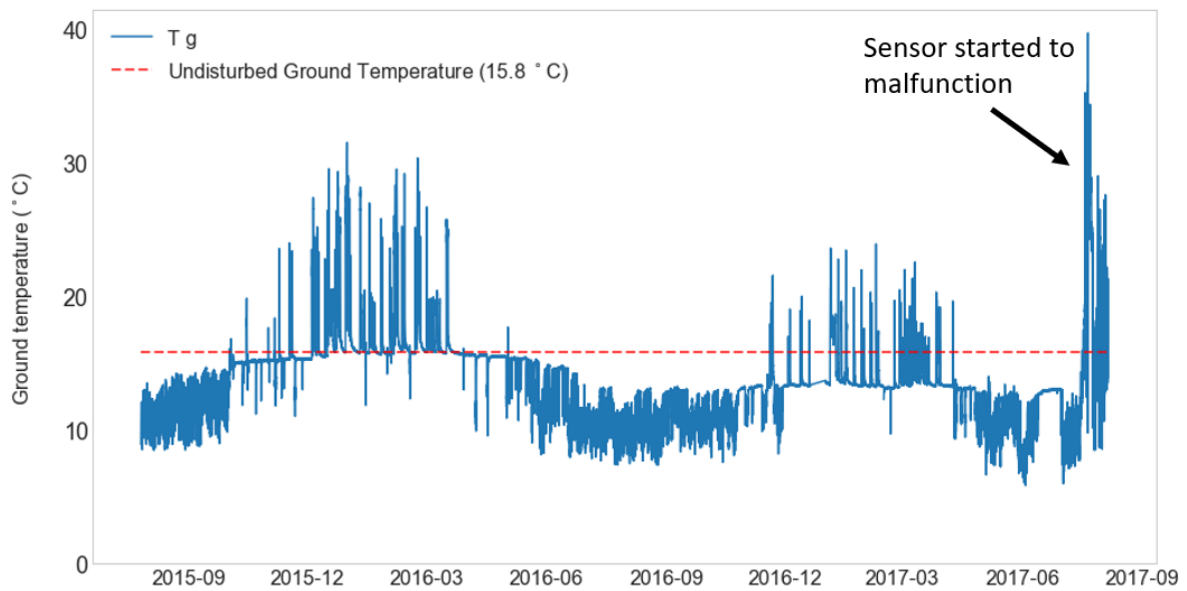


Figure B-25: Water temperature exiting and entering borehole form BH1

Footscray

Ground components: 2 ground heat exchangers, 55 m depth with double U-loop in each borehole

Heat pump size: 10 kW

Distribution system: Ducted heating and cooling

Status: Completed in May 2015



Figure B-26: (top row) installation of ground heat exchangers and thermal response test conducted in one of the boreholes, (middle row) heat pumps in the plant room and schematic of ducting installed

Instrumentation

- 8 Temperature sensors were installed around each ground heat exchangers with the configuration as outlined below.
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 1 flow meter to measure the flow of water into the ground.
- Power meter measures power consumption

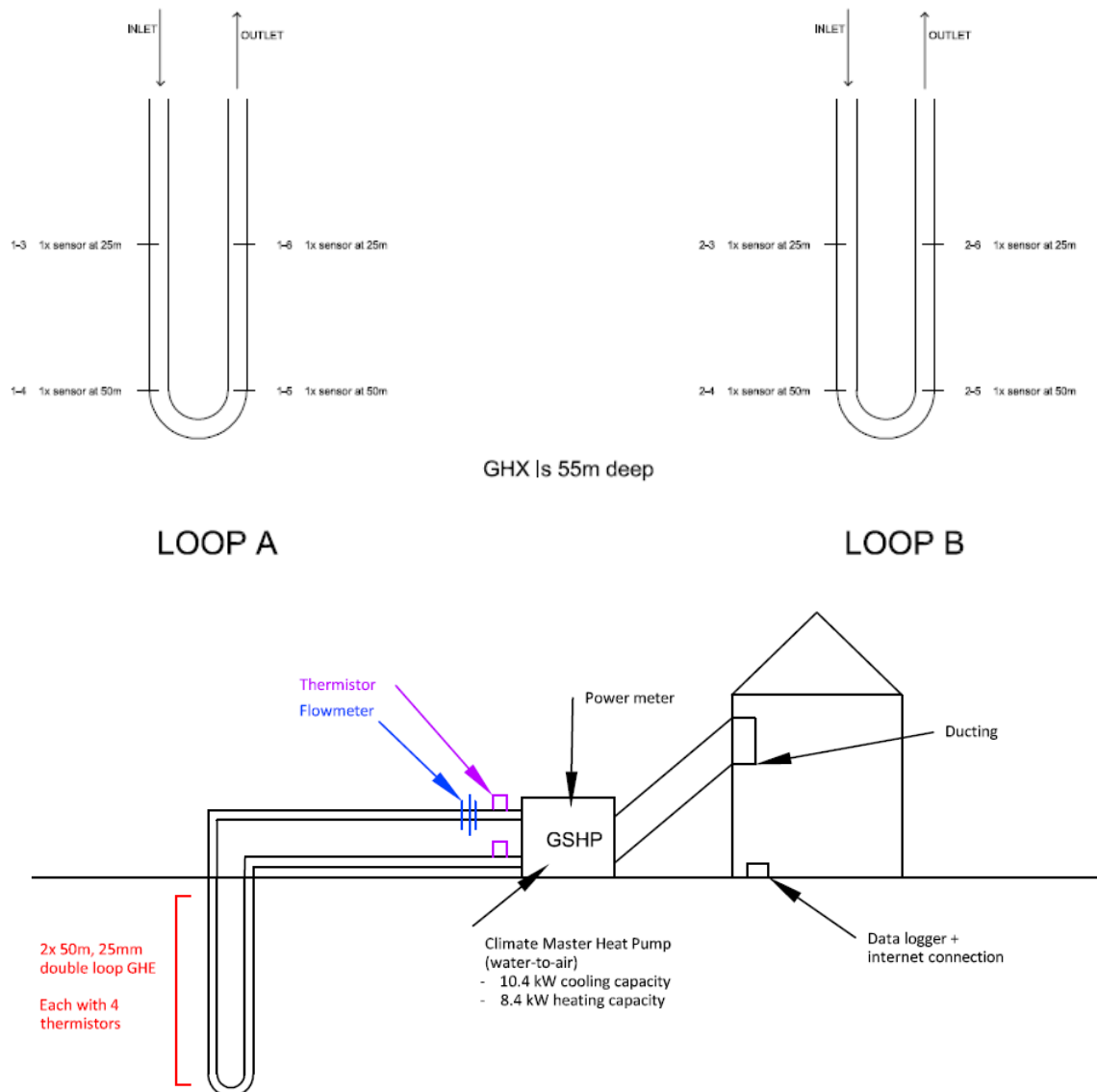


Figure B-27: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-8: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Footscray

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
May – Dec 2015	758	96	15	4,575	415	1,932	2.6
Jan – Dec 2016	676	86	9	3,451	364	1,686	2.3
Jan – Dec 2017	713	225	11	3,996	1,082	2,069	2.5
Jan – Jul 2018	171	43	4	976	192	476	2.5

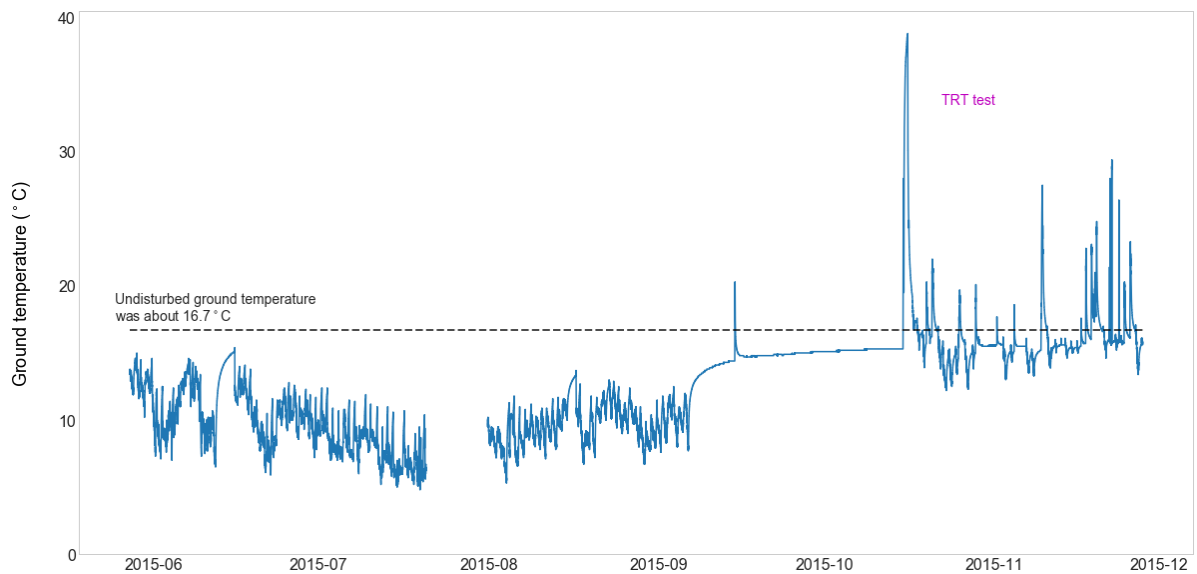


Figure B-28: Ground temperature monitored at borehole 1 (50 m depth)

Frankston

Ground components: 9 trenches of horizontal slinky GHEs. Each trench is 24m long with 25mm HDPE pipes.

Heat pump size: 22 kW

Distribution system: Floor hydronic heating, ceiling fan coil units and domestic hot water

Status: Ground loops are completed in July 2015. However, the project was not finished due to the owner's financial difficulties

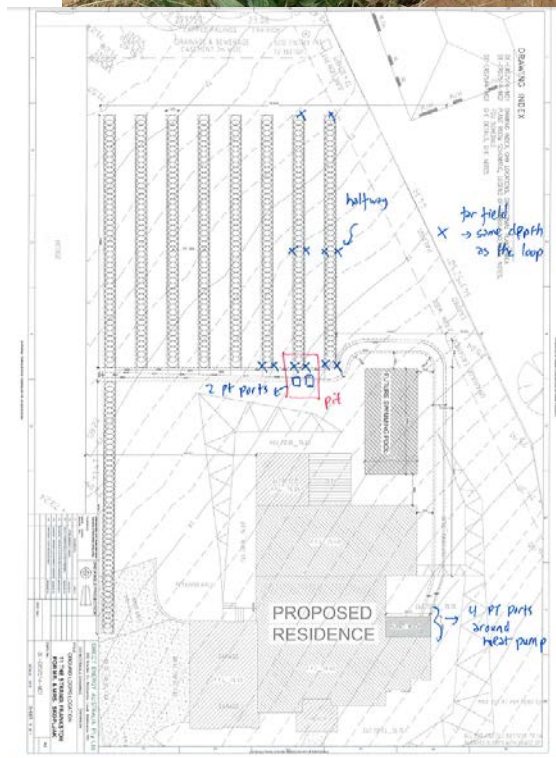


Figure B-29: (top row) Ground heat exchangers and ground loop sensors and (left) schematic of ground loop instrumentation

Inverloch

Ground components: 6 ground heat exchangers, 50 m depth with single U-loop in each borehole

Heat pump size: 18 kW

Distribution system: Floor hydronic heating and cooling and domestic hot water

Status: Completed December 2015

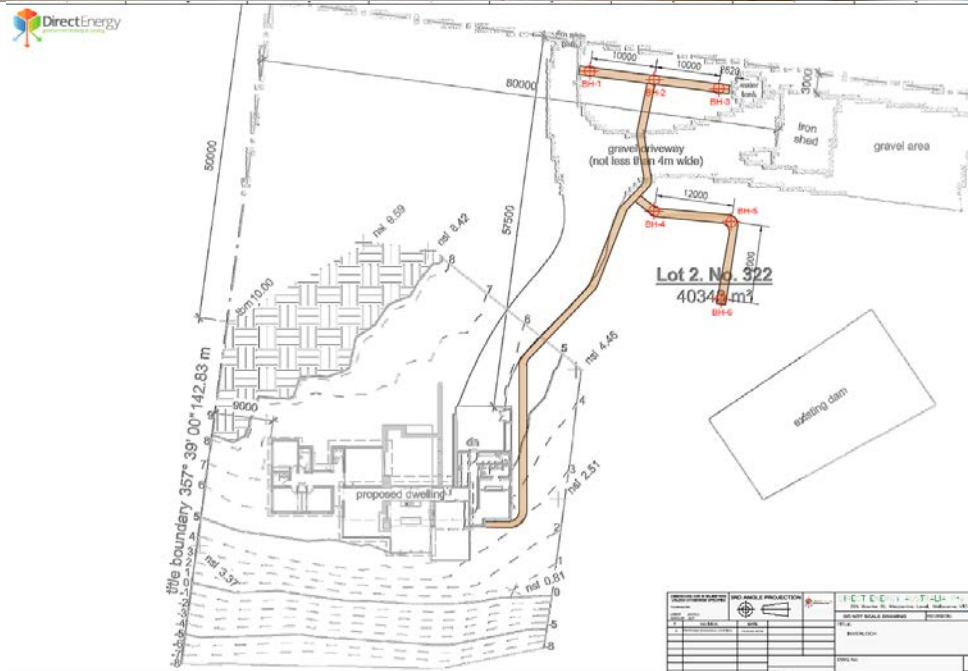


Figure B-30: (top row) heat pump and datalogger in the plant room, and (bottom row) schematic of ground loop location

Instrumentation

- 8 Temperature sensors were installed around each ground heat exchangers with the configuration as outlined below.
- 4 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

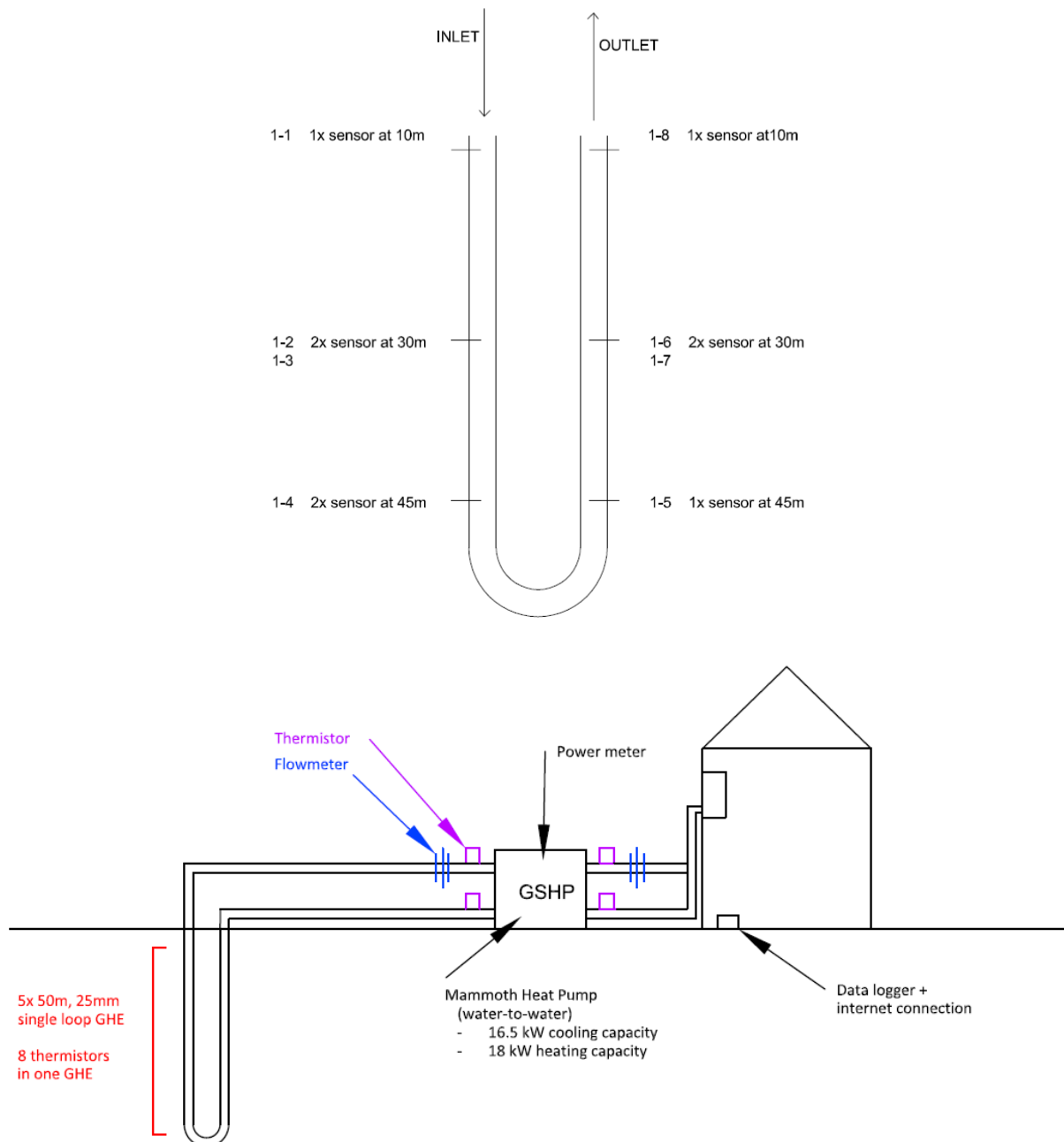


Figure B-31: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-9: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Inverloch

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Dec 2015	0	7	1	0	80	21	3.8
Jan – Dec 2016	1,084	184	14	11,562	1,873	3,904	3.4
Jan – Dec 2017	1,446	293	20	15,452	3,179	5,462	3.4
Jan – May 2018	95	177	8	918	1,932	817	3.5

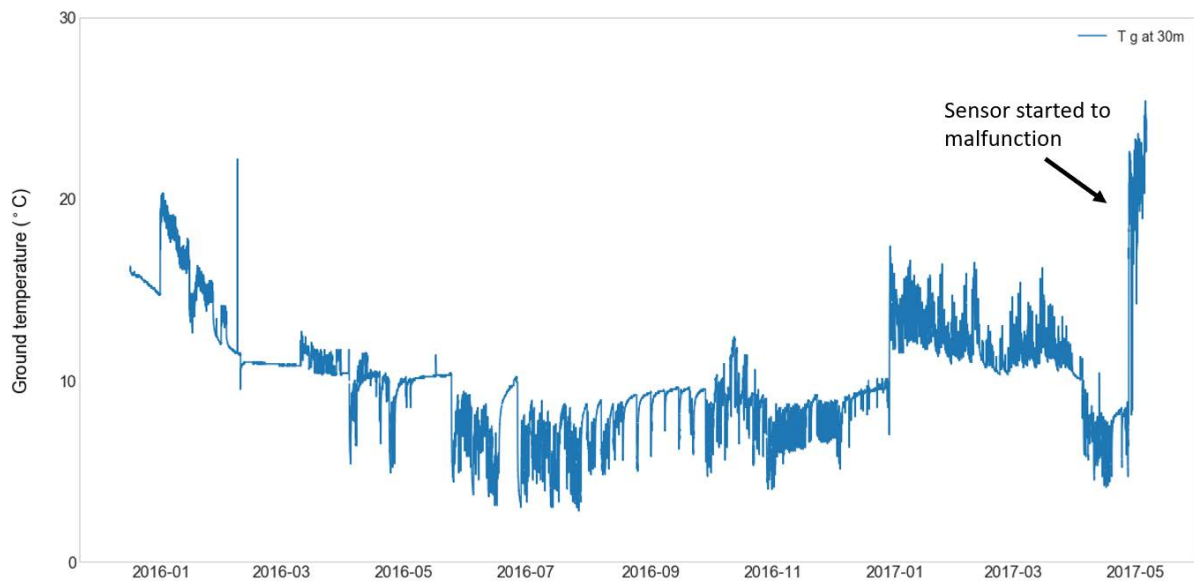


Figure B-32: Ground temperature monitored at borehole 1 (30 m depth)

Kangaroo Ground 1

Ground components: 6 copper loop GHEs, 30m deep.

Heat pump size: 14 kW

Distribution system: Hydronic heating and ceiling fan coil units

Status: Completed in 2013. But monitored data is limited due to the instrumentation installed

Instrumentation

- 2 of the copper loops are monitored at 15m and 30m
- 1 Flow meter to measure the flow of water into the building.
- Power meter measures power consumption



Figure B-33: Heat pump and water tank installed

Kangaroo Ground 2

Ground components: 9 trenches of horizontal slinky GHEs. Each trench is 36m long with 25mm HDPE pipes.

Heat pump size: 16 kW

Distribution system: Hydronic heating systems and wall split system for cooling

Status: Completed in September 2016



Figure B-34: (top row) trench where the ground loops were installed, and (bottom row) heat pump and data logger set up

Instrumentation

- 13 Temperature sensors were installed around each ground heat exchangers with the configuration as outlined below.
- 4 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

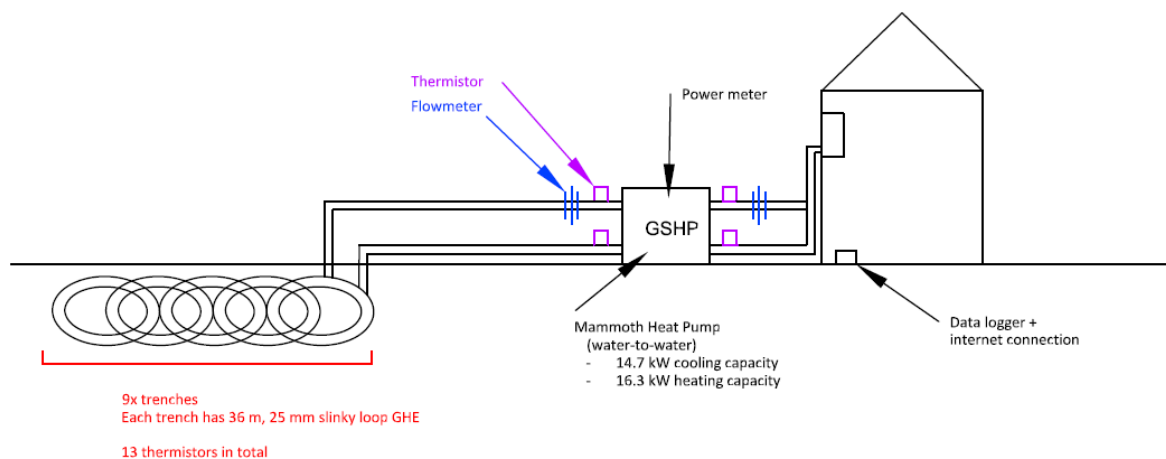
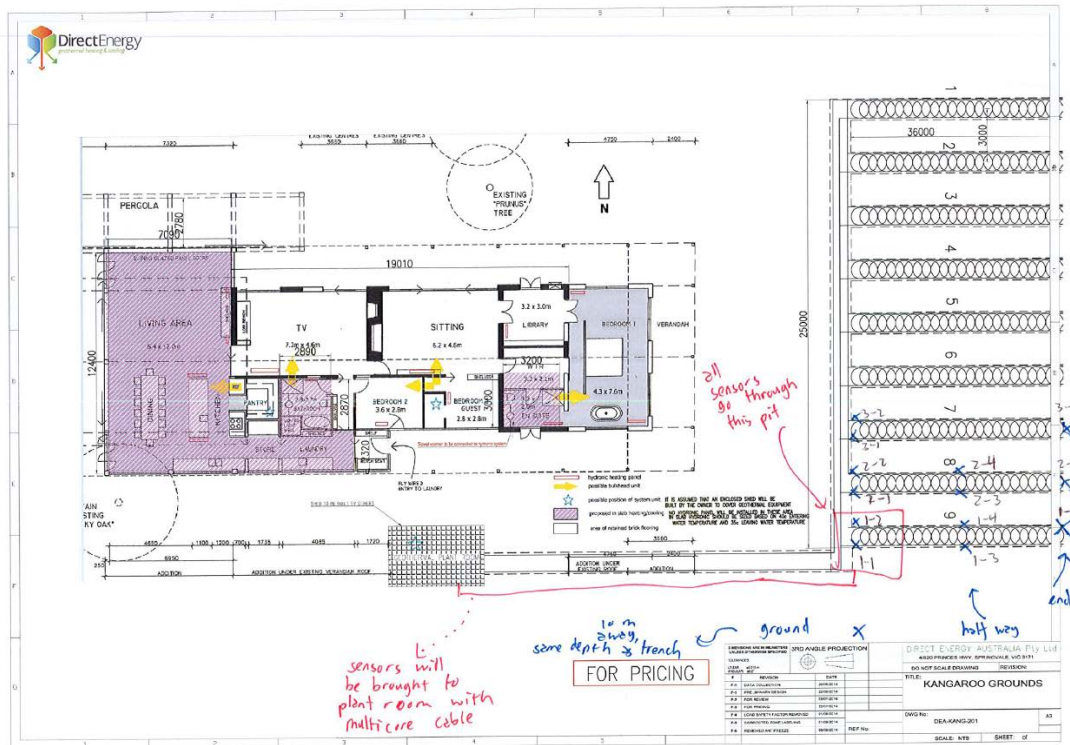


Figure B-35: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-10: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Kangaroo Ground 2

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Sep – Dec 2016	144	79	8	1,094	825	407	4.7
Jan – Nov 2017	576	223	9	4,496	2,208	1,498	4.5

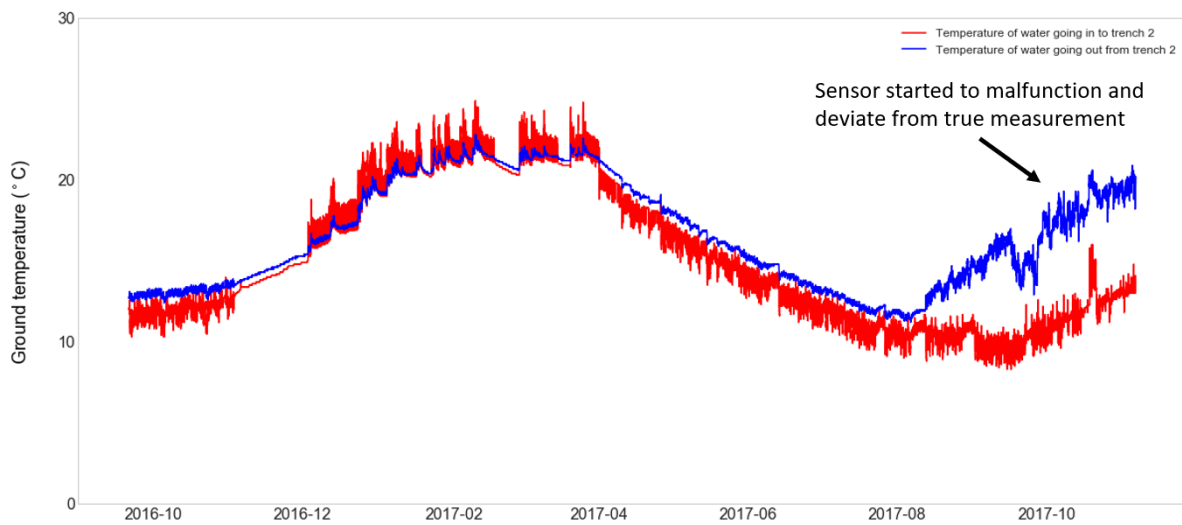


Figure B-36: Ground temperature monitored from trench no 2

Main Ridge

Ground components: 8 trenches of horizontal slinky GHEs. Each trench is 40 m long with 25mm HDPE pipes.

Heat pump size: 22 kW

Distribution system: Hydronic heating systems and domestic hot water. No cooling

Status: Completed in September 2015



Figure B-37: (top row) slinkies ground heat exchangers installation and instrumentation (bottom row) heat pump and data logger set up and the property that is heated and cooled

Instrumentation

- 16 temperature sensors were installed at the inlet and outlet of each trench.
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 2 flow meters to measure the flow of water into the ground and into the building.
- Power meter measures power consumption

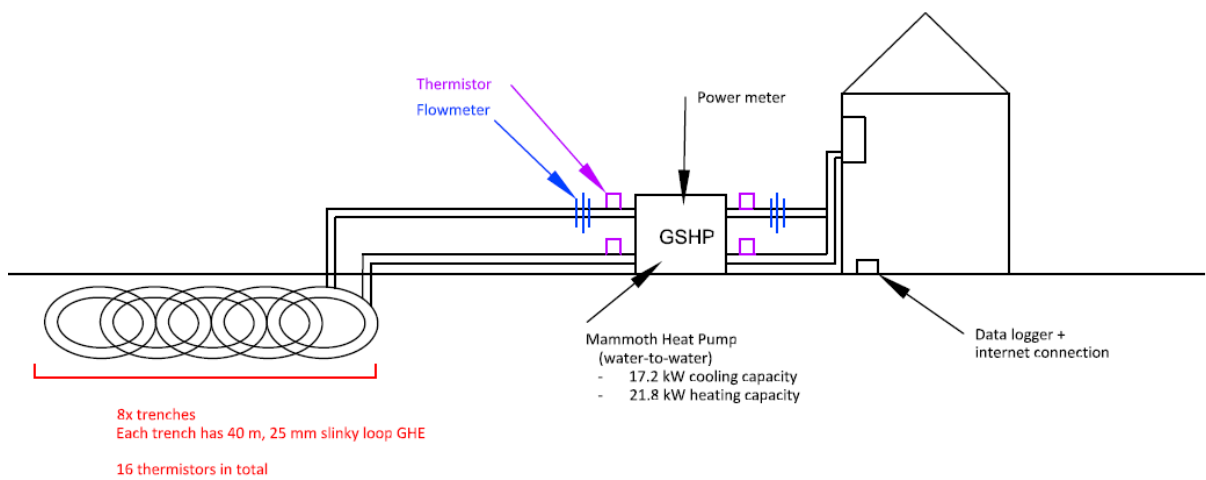
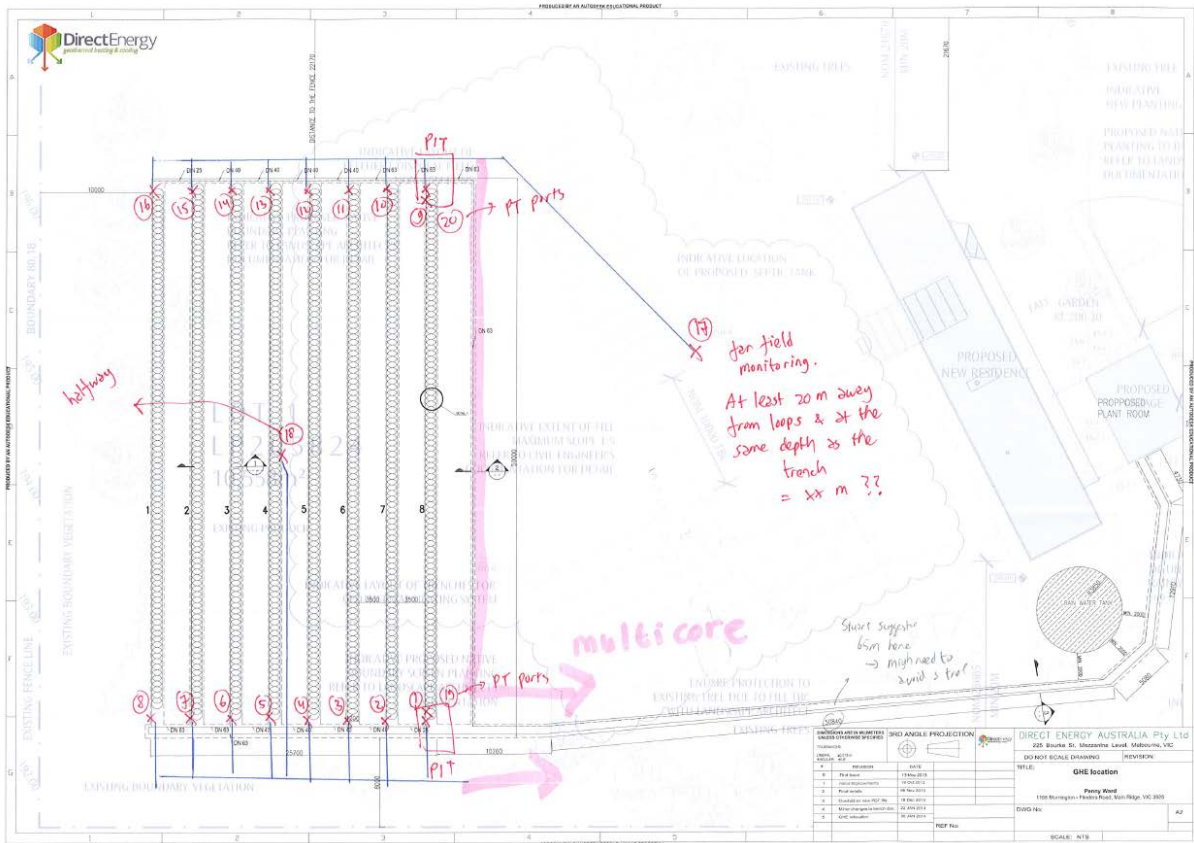


Figure B-38: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-11: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Main Ridge

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
Sep – Dec 2015	141	0	5	2,383	0	656	3.6
Jan – Dec 2016	487	0	6	8,293	0	2,295	3.6
Jan – Dec 2017	369	0	4	5,822	0	1,712	3.4
Jan 2018	16	0	2	247	0	73	3.4

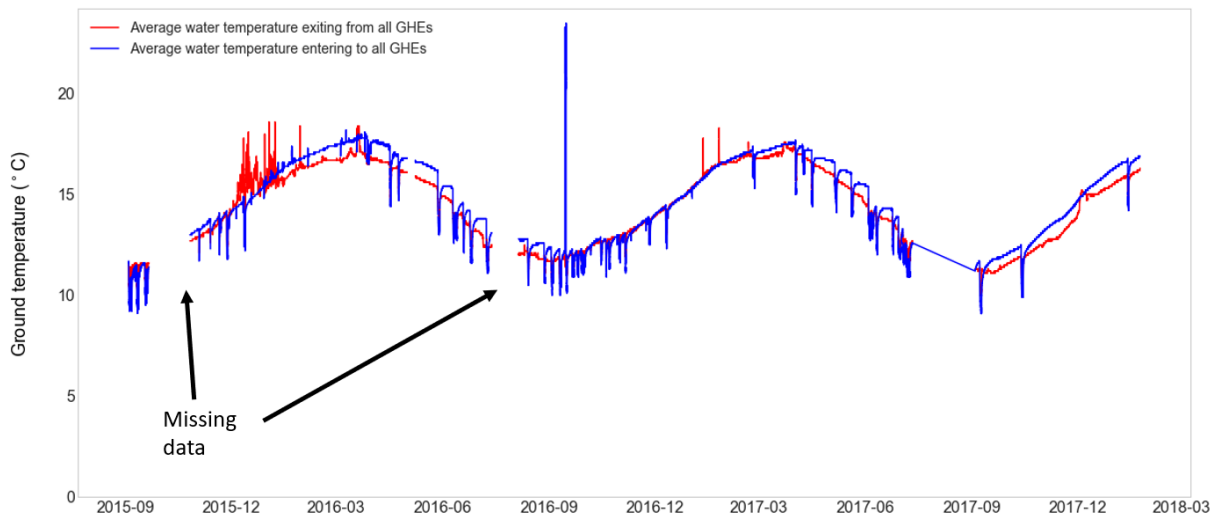


Figure B-39: Ground temperature monitored from all ground heat exchangers

Mildura

Ground components: 2 ground heat exchangers, 65 m depth. One borehole with single U-loop and the other borehole with double U-loop

Heat pump size: 6 kW

Distribution system: Ducted heating and cooling

Status: Installation completed in 2016, but heat pump malfunctioned at the time. Hence, it was difficult to monitor this further.

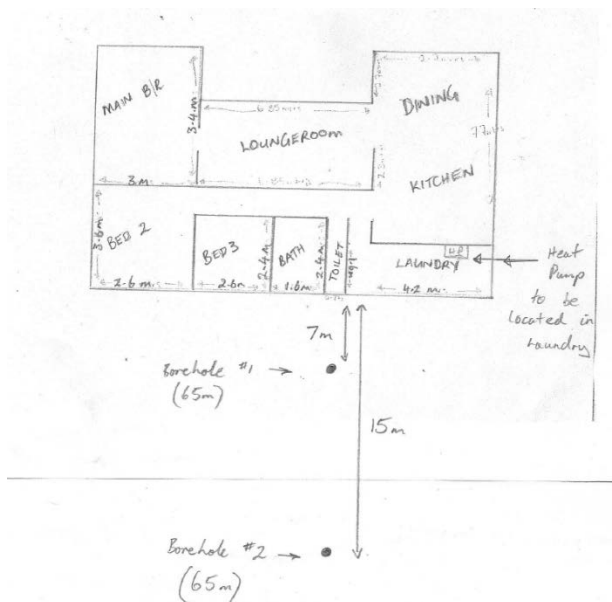
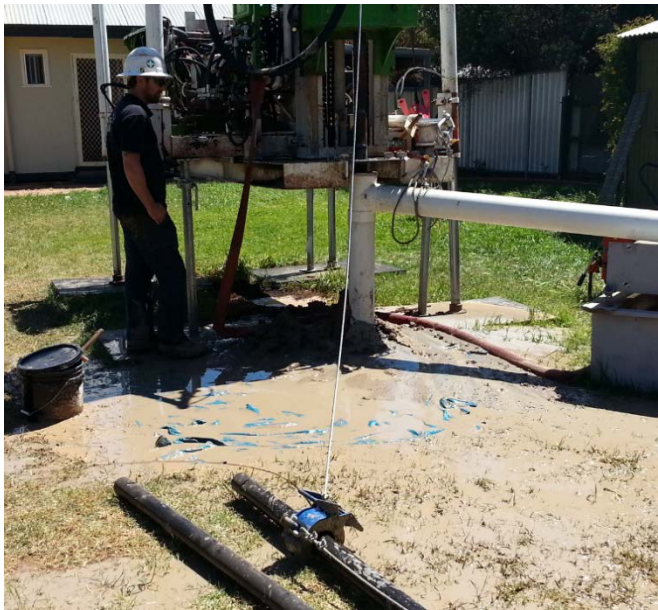


Figure B-40: (top row) drilling of ground heat exchangers installation and heat pump installed (bottom row) schematic of ground heat exchangers location

Instrumentation

- 11 temperature sensors were installed in 1 ground heat exchanger.



Figure B-41: Instrumentation schematic for the ground heat exchangers

Monbulk

Ground components: 27 energy piles GHEs, each pile is 6m deep with 25mm HDPE pipes and contain 3 loops, which are connected in series.

Heat pump size: 20 kW each and 2 heat pumps are installed

Distribution system: Hydronic heating and ceiling fan coil units

Status: Installation completed in November 2016. However, failure in instrumentation has limited the amount of data that can be analysed



Figure B-42: (left) energy piles to be installed and (right) with instrumentation

Instrumentation

7 piles were instrumented (piles no 19-25), at the following locations:

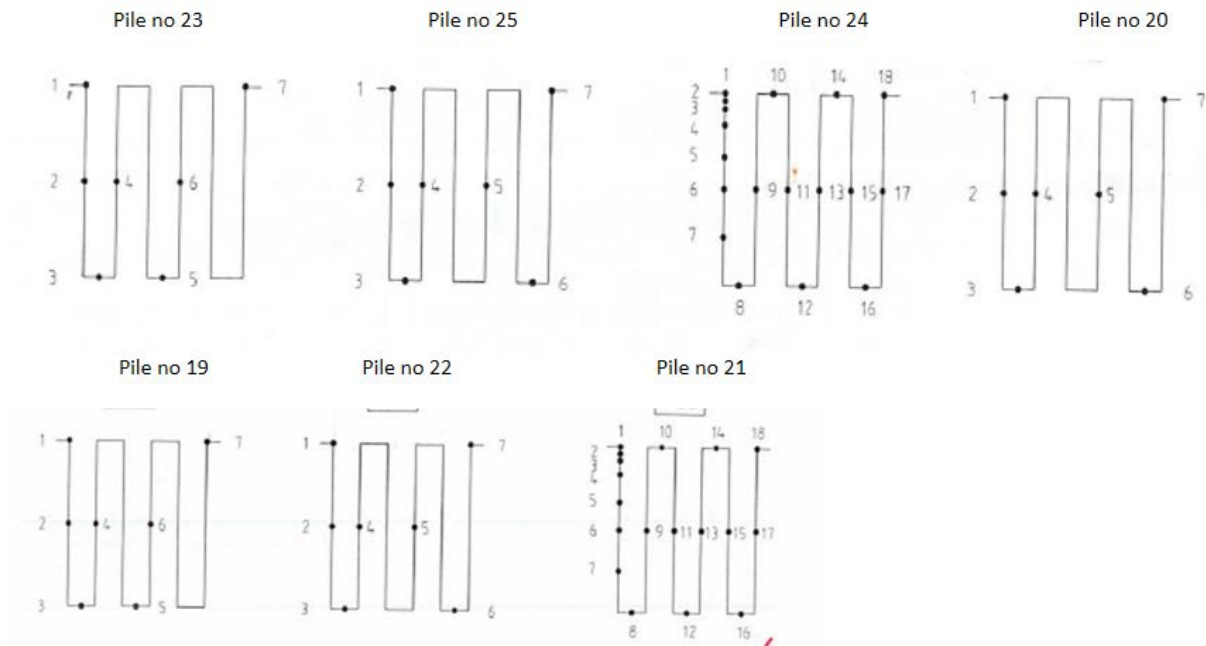


Figure B-43: schematic of instrumentation in the energy piles

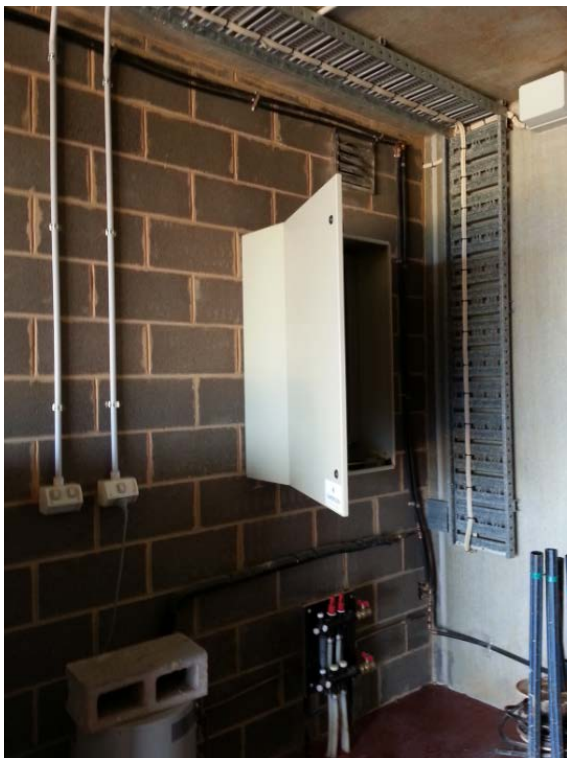


Figure B-44: data logger installed in the plant room

GSHP systems usage summary

GSHP performance data is not available for this property due to the limited instrumentation installed. Despite that, ground temperature response was available since there were some thermistors installed.

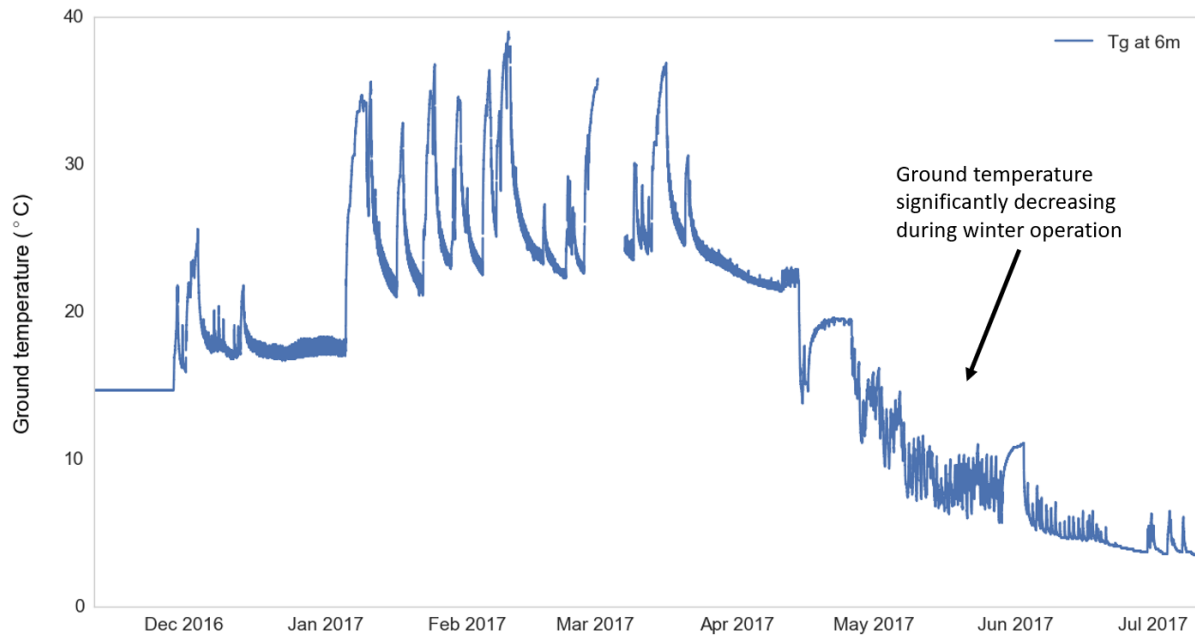


Figure B-45: ground temperature measured in one of the energy piles under thermal load applied by the occupants

Mulgrave

Ground components: 3 ground heat exchangers with single U-loop. One ground heat exchanger is at 50 m deep and the other 2 are at 25 m deep.

Heat pump size: not installed

Distribution system: not installed

Status: Ground loop installation was completed in early 2015, but the project was abandoned shortly afterwards where the property owner reneged on his promise



Figure B-46: (left) drilling of ground heat exchangers and (right) ground heat exchangers installed

GSHP systems usage summary

Although the project was abandoned, temporary ground temperature monitoring was set up

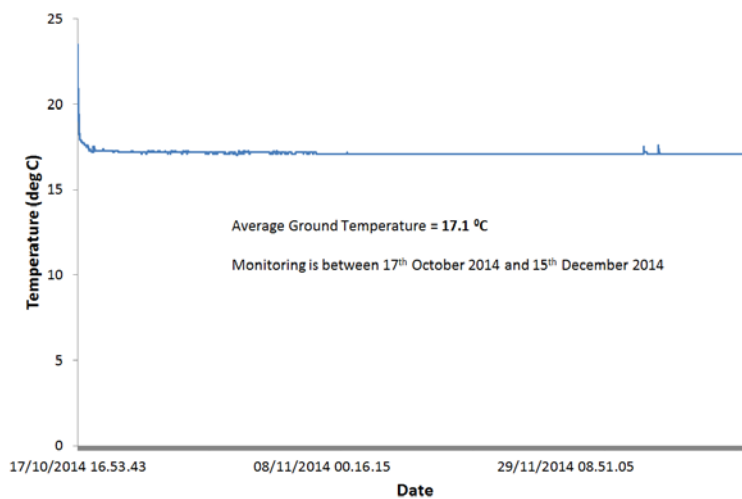


Figure B-47: ground temperature monitored at 25 m depth

Murrindindi

Ground components: 4 trenches of horizontal GHEs. Each trench is 50m long and has 2 horizontal GHE circuits with 25mm HDPE pipes. Also 4 coils of 25mm HDPE pipes in the dam, each coil is 100m.

Heat pump size: 13 kW

Distribution system: Ducted heating and cooling

Status: Completed in December 2014. However, limited data was collected due to data logger limitation



Figure B-48: (top row) header pipes for horizontal ground heat exchangers and installation of pond loops, and (bottom row) heat pump and monitoring equipment

Instrumentation

- 15 temperature sensors were installed at various location in-ground heat exchangers
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- 1 flow meter was installed which measures the flow of water into the loops in the dam.
- 1 flow meter was installed which measures the flow of water into the ground and into the building.
- Power meter measures power consumption

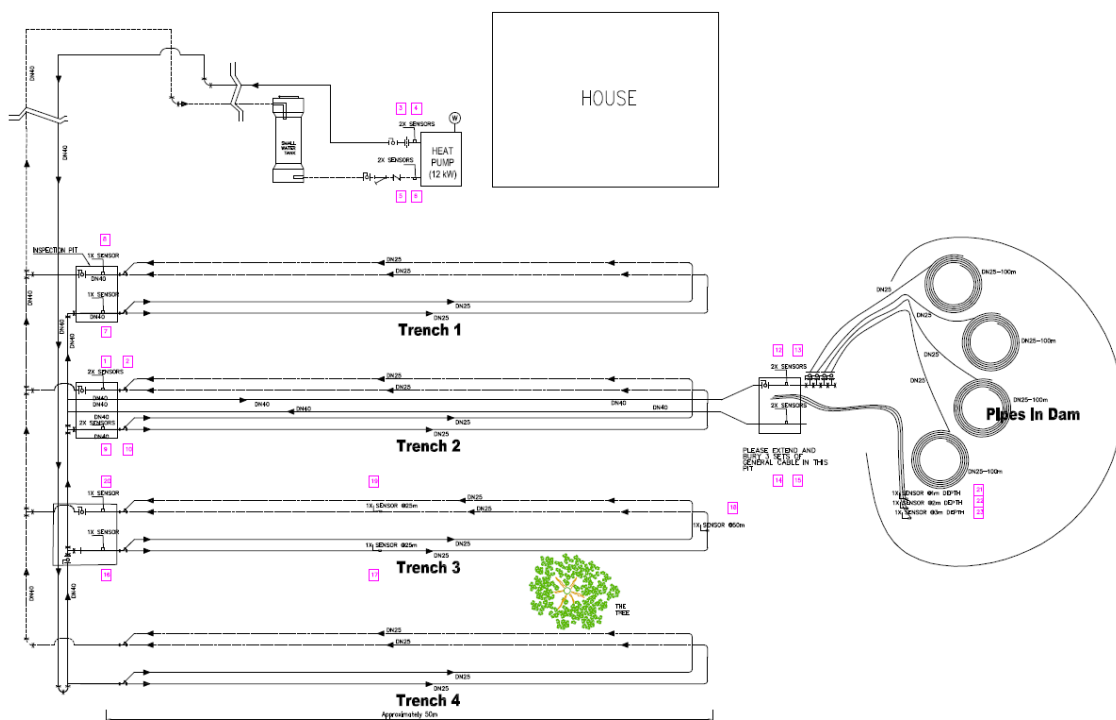


Figure B-49: schematic of instrumentation installed on the horizontal GHEs and pond loops

Parkville

Ground components: 5 ground heat exchangers, 50 m depth with double U-loop in each borehole

Heat pump size: 32 kW

Distribution system: Three wall split systems for heating and cooling

Status: Completed in 2015, but limited data are available for monitoring. Data from this property is presented in Dr Amir Kivi's thesis.

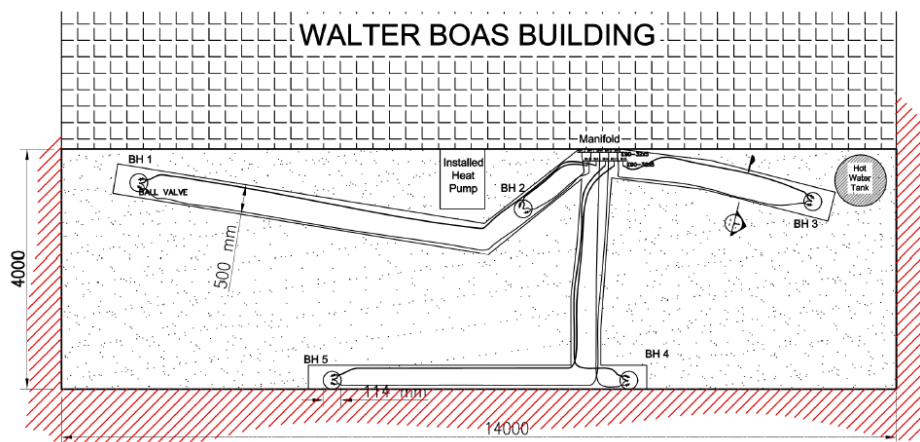


Figure B-50: (top row) drilling and installation of ground loops, (middle row) pit with ground loops, instrumentation and location of heat pumps and data logger, and (bottom row) schematic of ground loops location

Instrumentation

- Over 100 ground temperature sensors were installed at various depth in all 5 GHEs.
- In each pit, 2 temperature sensors were installed with a saddle fitting to monitor the water temperature directly. 1 fitting was installed in the inlet, while the other is in the outlet.
- In the plant room, 5 flow meters were installed to monitor the flow to each GHE.
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- A power meter was installed to monitor the electricity consumption of the heat pump.

Thornbury

Ground components: 2 ground heat exchangers, 50 m depth with double U-loop in each borehole

Heat pump size: 6 kW

Distribution system: Two wall split systems for heating and cooling

Status: Completed in May 2015



Figure B-51: (top row) drilling and installation of ground heat exchangers and (bottom row) location of thermal response test pit and the heat pump

Instrumentation

- 8 Temperature sensors were installed in 2 Ground heat exchangers as outlined below.
- 2 flow meters were installed which measures the flow of water into the ground and into the building.
- 2 temperature sensors each were installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- Power meter measures the power consumption of the heat pumps

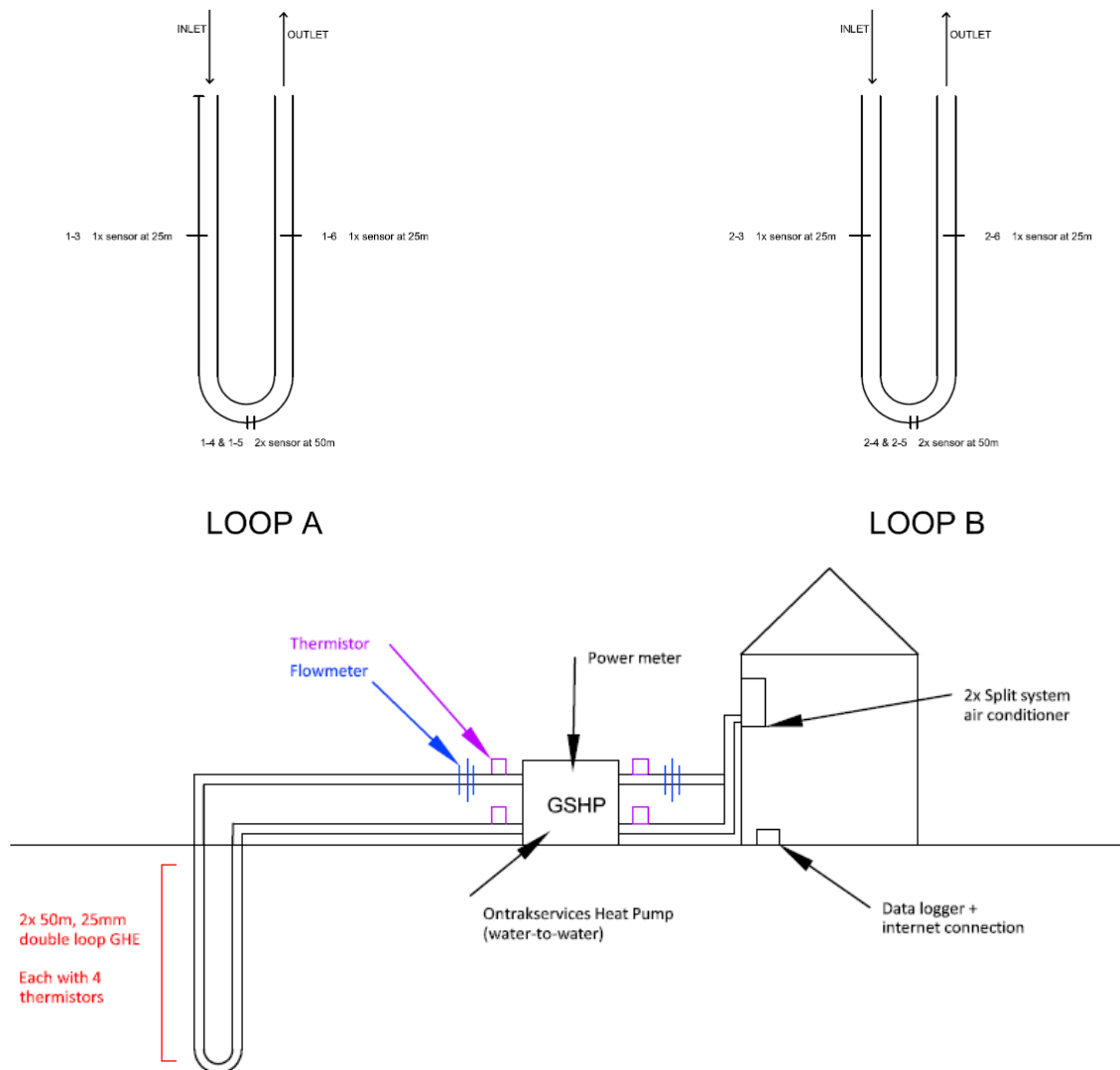


Figure B-52: (top row) Instrumentation schematic for the ground heat exchangers and (bottom row) instrumentation schematic of the overall instrumentation

GSHP systems usage summary

Table B-12: Summary of usage hours, heating and cooling energy provided to the building and total electrical energy used in Thornbury

Monitored period	Total usage (hours)		Run time fraction (%)	Total energy provided to the building (kWh)		Total electrical energy used (kWh)	SPF
	Heating	Cooling		Heating	Cooling		
May – Dec 2015	870	178	18	2,207	210	1,526	1.6
Jan – Dec 2016	117	417	6	149	452	427	1.4
Jan – Dec 2017	258	220	6	569	228	422	1.9
Jan – Feb 2018	0	43	3	0	70	37	1.9

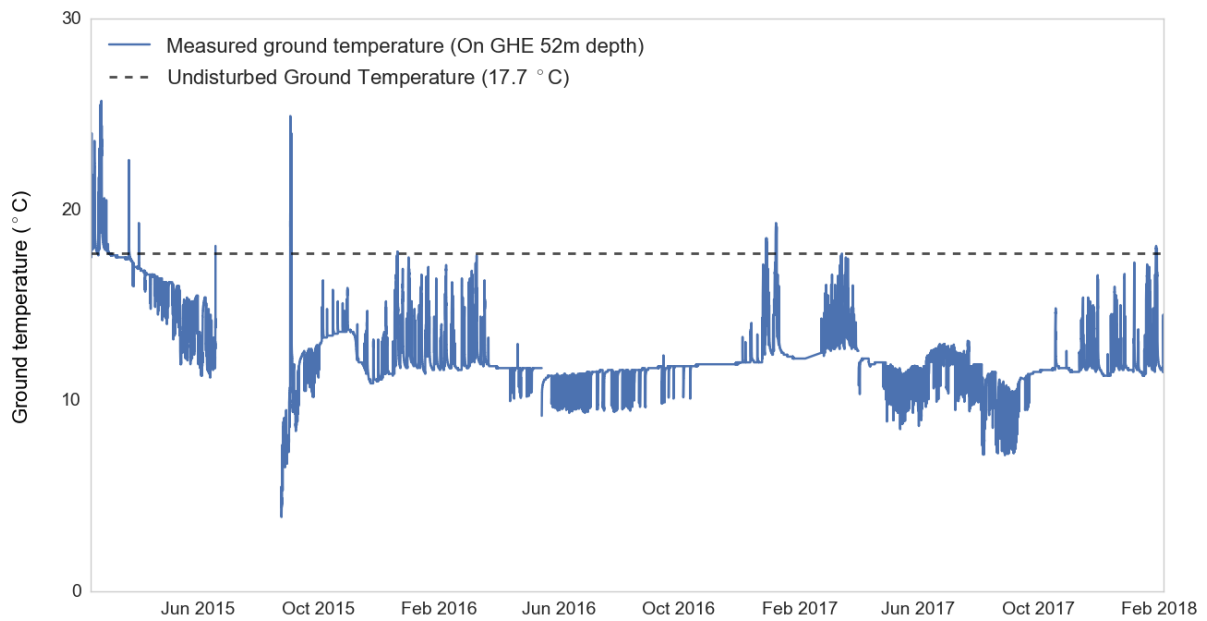


Figure B-53: ground temperature measured

Toorak

Ground components: 15 copper loop GHEs, 30m deep.

Heat pump size: 21 kW each and 2 heat pumps are installed

Distribution system: Hydronic heating systems, wall split system for cooling, domestic hot water heating and pool heating

Status: Completed in 2013. But monitored data is limited due to the instrumentation installed

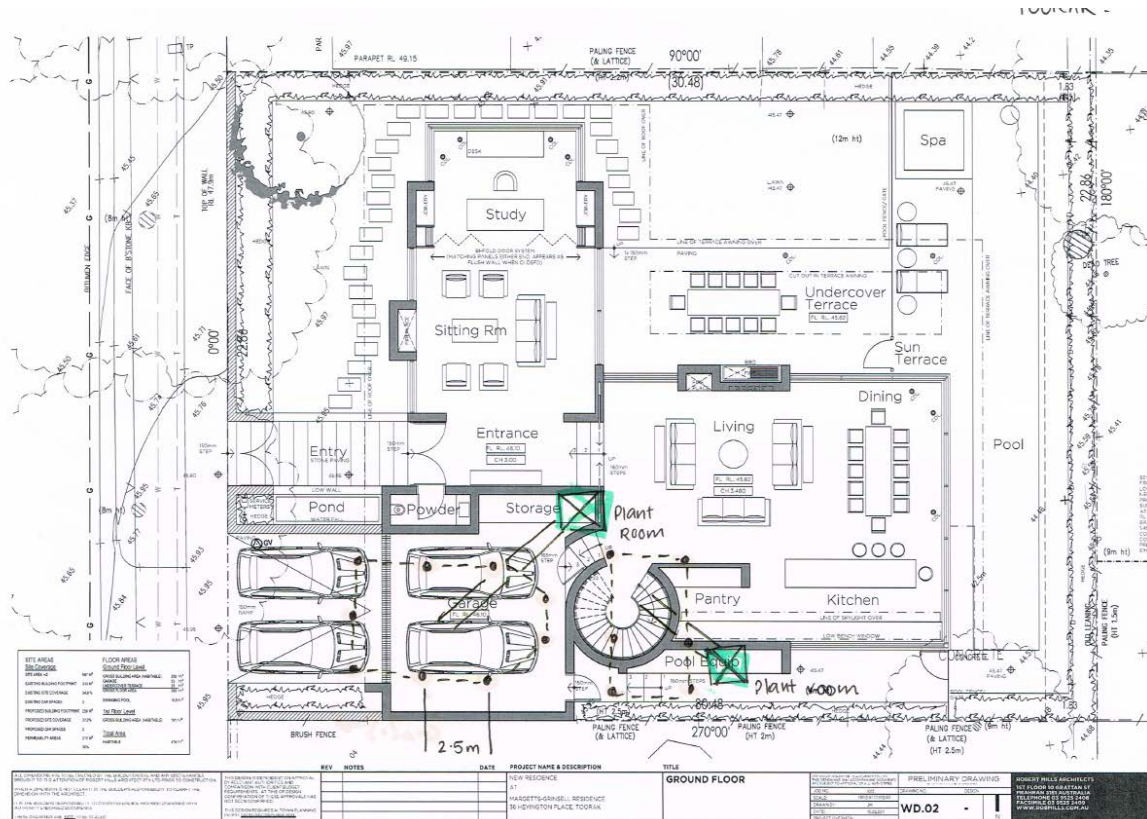


Figure B-54: schematic of copper loops location

Instrumentation

- 4 loops are instrumented with 2 thermistors at 15 m and 30 m depth
- 6 thermistors are installed around the heat pump to measure the temperature of the refrigerant flowing in and out from the heat pump
- 2 flow meters are measured to measure water flow rate supplying heating to the pool and hot water

Other instrumentation needs to be installed for conducting a detailed analysis of the GSHP system performance

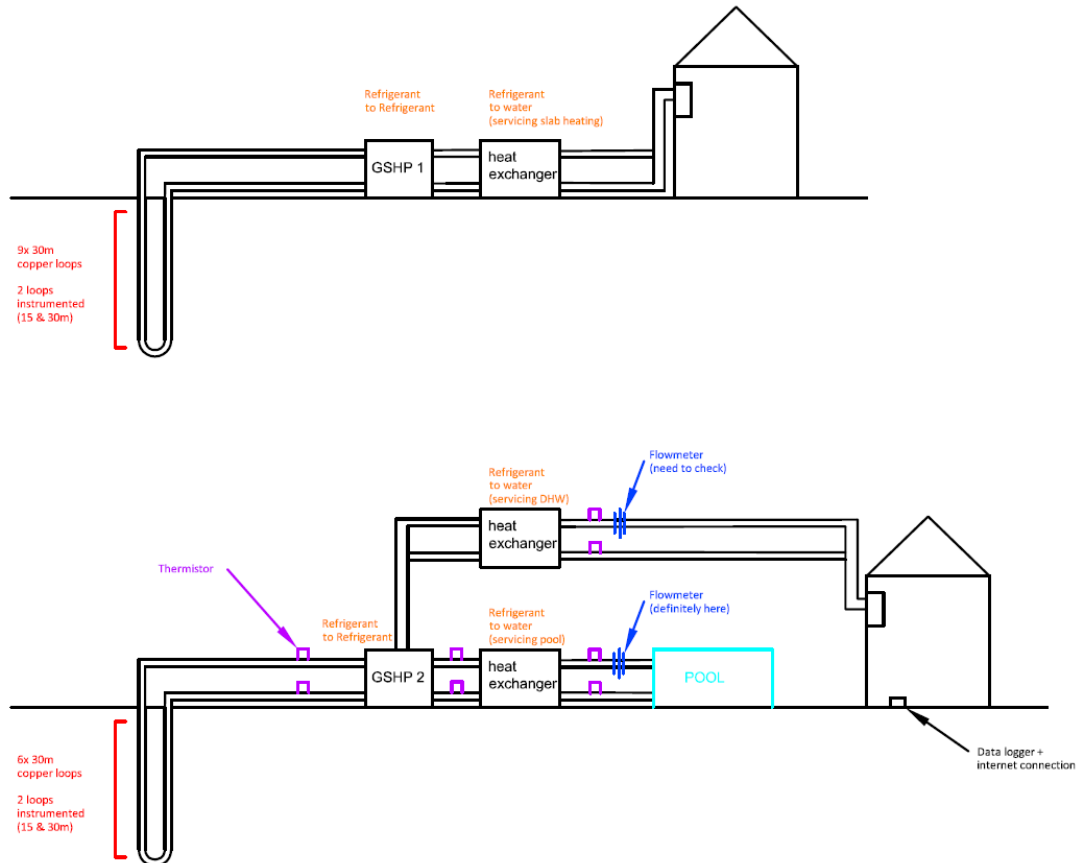


Figure B-55: instrumentation schematic of the overall instrumentation

Wangaratta

Ground components: 6 ground heat exchangers, 75m depth with single U-loop in each borehole

Heat pump size: 21 kW

Distribution system: Hydronic heating systems and domestic hot water

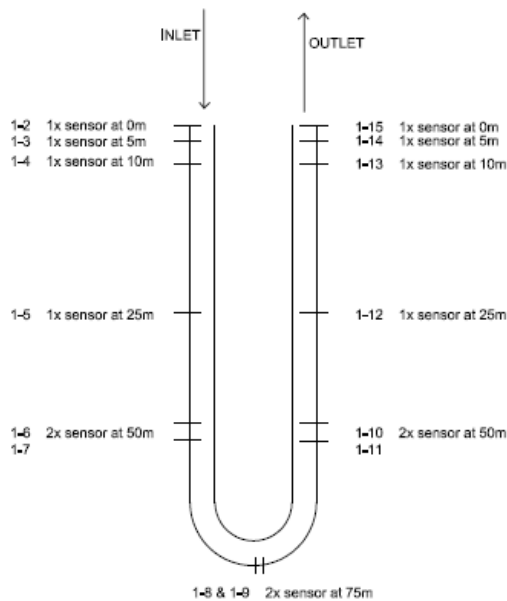
Status: Completed in late 2016. But the monitoring system was not installed due to the lack of usage at the house.



Figure B-56: Drilling and installation of instrumented ground loops

Instrumentation

- 14 Temperature sensors were installed in 1 ground heat exchanger as outlined below
- 2 flow meter will be installed to monitors the flow of water into the ground and into the building.
- 2 temperature sensors each will be installed to measure the temperature of the water going into the heat pump and out from the heat pump.
- A power meter will be installed to measure power consumption



LOOP A

Figure B-57: Instrumentation schematic for the ground heat exchangers

Appendix C

Sample Python codes used throughout this thesis

Sample Python codes used for data analysis in the SEPD project

Part 1 – Import data, cleaning & combining with current master data
(using the project in Ashburton as the example)

import necessary python module

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.dates as mdates
import os
import seaborn as sns; sns.set_style("whitegrid")
%matplotlib inline
```

import new data

```
os.chdir("U:/IE/Geothermal/Project/Ashburton/05. data/03. new txt files to add to current master data")
data1 = pd.read_csv('new-XJP60D.txt', sep="\t", skiprows=2, header = 0)
data2 = pd.read_csv('new-XJP60D (1).txt', sep="\t", skiprows=2, header = 0)
data3 = pd.read_csv('new-XJP60D (2).txt', sep="\t", skiprows=2, header = 0)
#data4 = pd.read_csv('WATERMETER_20131001.txt', sep="\t", skiprows=2, header = 0)
data6 = pd.read_csv('power meter.txt', sep="\t", skiprows=2, header = 0)
```

cleaning new data

```
data1 = data1[data1.Time != 'LOADOK'][['Time', 'Pb 1', 'Pb 2', 'Pb 4', 'Pb 5', 'Pb 6']]
data2 = data2[data2.Time != 'LOADOK'][['Time', 'Pb 1', 'Pb 2', 'Pb 4', 'Pb 5', 'Pb 6']]
data3 = data3[data3.Time != 'LOADOK'][['Time', 'Pb 1', 'Pb 2', 'Pb 3', 'Pb 4', 'Pb 5', 'Pb 6']]
data6 = data6[data6.Time != 'LOADOK'][['Time', 'Total Active PW', 'Total kWh']]
```

```
data1['Time'] = pd.to_datetime(data1['Time'], format='%d/%m/%Y %H.%M.%S')
data1v2 = data1.set_index('Time').resample('10T', how = 'mean')
```

```
data2['Time'] = pd.to_datetime(data2['Time'], format='%d/%m/%Y %H.%M.%S')
data2v2 = data2.set_index('Time').resample('10T', how = 'mean')
```

```
data3['Time'] = pd.to_datetime(data3['Time'], format='%d/%m/%Y %H.%M.%S')
data3v2 = data3.set_index('Time').resample('10T', how = 'mean')
```

```
data6['Time'] = pd.to_datetime(data6['Time'], format='%d/%m/%Y %H.%M.%S')
data6v2 = data6.set_index('Time').resample('10T', how = 'mean')
```

combine new data into one dataframe

```
new_data = pd.concat([data1v2, data2v2, data3v2, data6v2], axis=1)
new_data = new_data.reset_index()
new_data.columns = ['Date Time', 'B1-5', 'B1-6', 'B1-4', 'B1-3', 'B1-2', 'G -> HP', 'HP -> G', 'B2-4', 'B2-3', 'B2-2', 'B2-5', 'B2-8', 'B2-10', 'B2-7', 'B2-6', 'B2-9', 'power consumed by GSHP (kW)', 'Energy consumed by GSHP (kWh)']
```

Load master data

```
os.chdir("U:/IE/Geothermal/Project/Ashburton/05. data/01. python df master data RAW")  
data = pd.read_pickle('new_master_data')
```

Combine new data with master data

```
#finding index in the new data that has not been added to master data  
value_to_find = data['Date Time'].iloc[-1]  
Min = new_data['Date Time'] <= value_to_find  
idx_Min = new_data.ix[Min, 'Date Time'].idxmax()
```

```
data_to_add = new_data.iloc[idx_Min +1::]
```

```
new_master_data = pd.concat([data,data_to_add], ignore_index=True)
```

Saving the new master data

```
os.chdir("U:/IE/Geothermal/Project/Ashburton/05. data/01. python df master data RAW")  
new_master_data.to_pickle('new_master_data')
```

Run analysis

```
os.chdir("U:/IE/Geothermal/Project/Ashburton/05. data")  
%run Asburton_analysis.py
```

Part 2 – Analysis

import necessary python module

```
import pandas as pd  
import numpy as np  
import matplotlib.pyplot as plt  
import matplotlib.dates as mdates  
import time  
import os  
#matplotlib inline
```

import data

```
print("Importing data from excel...")
```

Importing master data from excel

```
os.chdir("U:/IE/Geothermal/Project/Ashburton/05. data/01. python df master data RAW")  
Ashburton_data = pd.read_pickle('new_master_data')
```

cleaning data

```
print("Cleaning data...")
```

#convert the datetime

```
Ashburton_data['year'] = Ashburton_data['Date Time'].dt.year  
Ashburton_data['month'] = Ashburton_data['Date Time'].dt.month
```

```

# analysis
print("Generating additional variable for analysis...")

#calculating delta T G and T B (temperature difference between inlet and outlet at the ground side
#and the building side)
Ashburton_data['delta tg']=Ashburton_data['G -> HP']-Ashburton_data['HP -> G']
Ashburton_data['delta tb']=Ashburton_data['HP -> B']-Ashburton_data['B -> HP']

#calculating power supplied by the ground and to the building
# This filtering is to ensure that GSHP really operating.
# Exclude when there is a small flow measurement (indicate error) or low power consumption by
# GSHP (standby power)

def gpower(c):
    if (c['power consumed by GSHP (kW)']>0.3) & (c['Fm G']>0.1) :
        return 4.2*c['delta tg']*c['Fm G']
    else:
        return 0

Ashburton_data['power from g'] = Ashburton_data.apply(gpower, axis = 1)

def bpower(d):
    if d['power from g'] == 0:
        return 0
    else:
        return d['power from g']+ d['power consumed by GSHP (kW)']

Ashburton_data['power to b'] = Ashburton_data.apply(bpower, axis = 1)

#calculating COP
def cop(e):
    if (e['power consumed by GSHP (kW)']>0.3) & (e['Fm G']>0.1) :
        return e['power to b'] / e['power consumed by GSHP (kW)']
    else:
        return 0

Ashburton_data['COP'] = Ashburton_data.apply(cop, axis = 1)

#calculating time delta
time_delta = 3600 / (Ashburton_data['Date Time'][1] - Ashburton_data['Date Time'][0]).seconds

#calculating if GSHP is in heating mode or cooling mode
def heatcool(f):
    if(f['power to b'] >= 0.1):
        return "heating"
    elif (f['power to b'] <= -0.1):
        return "cooling"
    else:
        return "none"

Ashburton_data['heatcool'] = Ashburton_data.apply(heatcool, axis = 1)

```

#calculating usage hours for heating and cooling use

```
usage_hours = Ashburton_data.groupby(['year','month','heatcool'])['heatcool'].count()/time_delta
usage_hours = usage_hours.unstack(level=-1)
usage_hours_on = usage_hours.drop(usage_hours.columns[-1], axis=1).round(0).fillna(0)
usage_hours_on.columns = ['Cooling usage (hours)','Heating usage (hours)']
```

#Calculating delta energy consumed and produced

```
Ashburton_data['delta_e_consumed'] = Ashburton_data['power consumed by GSHP (kW)'].abs()/time_delta
Ashburton_data['delta_e_produced'] = Ashburton_data['power to b'].abs()/time_delta
Energy_daily = pd.concat([Ashburton_data['year'],Ashburton_data['month'],\
    Ashburton_data['delta_e_produced'],Ashburton_data['delta_e_consumed'],\
    Ashburton_data['heatcool'],Ashburton_data['COP']
    ],axis=1)
```

```
datasub = Energy_daily[Energy_daily['COP'] != 0.0].groupby(['year','month','heatcool']).mean()
datasub2 = datasub.drop(datasub.columns[0:2], axis=1).unstack(level=-1)
datasub3 = Energy_daily.groupby(['year','month','heatcool']).sum()
datasub4 = datasub3.drop(datasub3.columns[1:3], axis=1).unstack(level=-1)
datasub5 = datasub3.drop(datasub3.columns[0], axis=1).drop(datasub3.columns[-1],
axis=1).unstack(level=-1)
```

#calculating monthly COP

```
ave_COP = abs(datasub2.drop(datasub2.columns[-1], axis=1)).round(3)
ave_COP.columns = ave_COP.columns.droplevel()
ave_COP.columns = ['COP cooling mode','COP heating mode']
```

```
E_produced = datasub4.drop(datasub4.columns[-1], axis=1)
E_produced.columns = E_produced.columns.droplevel()
```

```
E_consumed = datasub5.drop(datasub5.columns[-1], axis=1).sum(axis = 1)
```

```
E_analysis = pd.concat([E_consumed, E_produced], axis=1).round(0).fillna(0)
E_analysis.columns = ['E consumed (kWh)','Cooling E delivered (kWh)','Heating E delivered (kWh)']
```

cost comparison with other energy sources

```
# Assume air condition has COP 2.5, and gas heating efficiency 0.85
```

```
E_analysis['E needed as alt cooling']=E_analysis['Cooling E delivered (kWh)']/2.5
E_analysis['E needed as alt heating']=E_analysis['Heating E delivered (kWh)']/0.85
```

```
E_analysis['Estimated geothermal running cost'] = (E_analysis['E consumed (kWh)'] * 0.25).round(2)
E_analysis['Estimated running cost with conventional cooling energy'] = (E_analysis['E needed as alt cooling'] * 0.25).round(2)
E_analysis['Estimated running cost with conventional heating energy'] = (E_analysis['E needed as alt heating'] * 0.07).round(2)
```

```
# saving
os.chdir("U:/IE/Geothermal/Project/Ashburton/05. data/02. python df master data ANALYSED")
Ashburton_data.to_pickle('Ashburton master data')
usage_hours_on.to_pickle('usage_hours_on')
ave_COP.to_pickle('ave_COP')
E_analysis.to_pickle('Energy summary data')
print('data has been exported')
```

Sample Python codes used for HGSHP system analysis (Chapter 5 & 6)

Part 1 – ILS simulation based on Weeratunge et al, 2018

GSHP and ASHP parameter based on manufacturer datasheet

```
e2 = 0.0483
f2 = -0.0071
e1 = 0.3014
f1 = 0.0046

def getPower(d):
    if d['ground_load'] < 0:
        # cooling
        val = (e2 - f2*d.EWT_calc)
    else:
        # heating
        val = (e1 - f1*d.EWT_calc)
    return 1/val

def getPower2(d):
    val = (3.376 + 0.06*d.EWT_calc)
    return val

def getPowerASHP(e):
    if e['HD_boiler'] > 0:
        # heating
        val = 2.1829 + 0.0607*e.Temp
    else:
        if e['HD_rcac'] < 0:
            # cooling
            val = 4.0961 - 0.0492*e.Temp
        else:
            val = 0
    return val
```

ILS simulation to calculate EWT to the GSHP at each hour and hence also the CoP of GSHP and RCAC at each hour

```
A2 = 1/(4*np.pi*k)

a['q'] = a['ground_load']*1000/(L)
a['A_delta_q'] = -A2*a.q.diff()

a['u']=rb**2/(4*alpha2/24*a['Unnamed: 0'])
a['Wu']=-gamma - np.log(a.u)
a['delta_t'] = 0

# calc delta t
for m in range(1,len(a.Hour)):
    temp_a = a.A_delta_q[1:m+1]
    temp_b = a.Wu[1:m+1]
    temp_b = temp_b.iloc[::-1]
    delta_t_calc = np.dot(temp_a,temp_b).round(5)
    a.loc[m+1,'delta_t'] = delta_t_calc

# Calculate Tb
a['Tb_calc'] = Tg+a.delta_t
a.at[0, 'Tb_calc'] = 0

# Calculate Tf
a['Tf_calc'] = a.Tb_calc - Rb*a.q.shift()

# Calculate EWT to GSHP
a['EWT_calc'] = a.Tf_calc + a['ground_load'].shift()/(2*Cp*m1)

a['CoP'] = a.apply(getPower,axis=1)
a['Power_c_calc'] = 1/a['CoP']*a['ground_load']
#a['CoP'] = abs(a['ground_load']/a['Power_c_calc'])
CoP = a['CoP'].mean()

a['cop_rcac'] = a.apply(getPowerASHP,axis=1)
cop_rcac_temp = a['cop_rcac'].copy()
CoP_rcac = (cop_rcac_temp.replace(0,np.NaN)).mean()
```

Part 2 – HGSHP system analysis code, economic analysis

Part 2.1

Calculate peak hourly load and total energy at each city

class city:

```
def __init__(self, weather, heat_db, cool_db):
```

```
    # create a year of weather data (eg: for 2014)
```

```
    self.weather = weather
```

```
    self.heat_db = heat_db #99% design from ASHRAE table
```

```
    self.cool_db = cool_db #99% design from ASHRAE table
```

```
    self.mean_OAT = round(np.mean(self.weather.Temp),2)
```

```
    # design variables in degree C
```

```
    t_base_h = 17.5
```

```
    t_base_c = 17.5
```

```
    # Generate heating demand based on bin data
```

```
    HD_design_max = 10
```

```
    # Calculate peak heating and cooling load based on 99% heating and cooling designed temperature by ASHRAE
```

```
    self.PH = (t_base_h-self.heat_db)/max((t_base_h-self.heat_db),(self.cool_db-t_base_c))*HD_design_max
```

```
    self.PC = -(self.cool_db-t_base_c)/max((t_base_h-self.heat_db),(self.cool_db-t_base_c))*HD_design_max
```

```
    # Calculate the required thermal load
```

```
    self.weather['HD'] = np.where(self.weather.Temp >= t_base_h, (self.weather.Temp-t_base_c)/(self.cool_db-t_base_c)*self.PC,
```

```
                                (t_base_h-self.weather.Temp)/(t_base_h-self.heat_db)*self.PH)
```

```
    self.weather['HDv2'] = self.weather['HD'].clip(self.PH, self.PC)
```

```
    #calculate Tg as mean OAT + 2 deg C
```

```
    self.tg = self.mean_OAT + 2
```

```
    # Identify peak heating and cooling demand, annual heating and cooling energy and net annual energy
```

```
    self.peakH = self.weather.HDv2.max().round(1)
```

```
    self.peakC = self.weather.HDv2.min().round(1)
```

```
    self.aeH = round(self.weather.HDv2[self.weather.HDv2 >0].sum())
```

```
    self.aeC = round(self.weather.HDv2[self.weather.HDv2 <0].sum())
```

```
    self.aeN = self.aeH + self.aeC
```

Part 2.2

Calculate G function based on ILS

Set time for 6h, 1month and 10years. 1 is one day

t1 = 1/4

t2 = 30 + 1/4

t3 = 365*10 + 30 + 1/4

t = [t1,t2,t3]

Input

rb = 0.1145/2 # Borehole radius in m - measured /designed EBSS

r = rb

k = 2.5 # Thermal conductivity in W/mK - measured EBSS

rho = 2000 # Density in kg/m³ - estimated

cp = 800 # Specific heat capacity in J/kgK - measured MMRP

alpha2 = k/(rho*cp)*3600*24 # Thermal diffusivity in m²/day - calculated

Q0 = 1/(2*np.pi*rb) # normalised heat injection

C = np.exp(0.57722) # exponential of Euler's constant

Calculating G function

G = []

for time in t:

u3 = Q0 * rb / (2*k) * (np.log(4*alpha2*time/C/r**2) +
rb**2/(2*alpha2*time)*np.log(4*alpha2*time/C/r**2) +
(1/(4*alpha2*time)*(rb**2+r**2-2*rb**2*np.log(rb/r))))

G.append(u3)

R6h = G[0]

R1m = G[1]-G[0]

R10y = G[2] - G[1]

R6h, R1m, R10y

Input variables for GHE system design

Constants for ASHRAE design

Tp = 0 # temp penalty. No penalty as only a single GHE being considered

Calculating borehole thermal resistance

hconv = 1000 # internal convection coefficient in W/m²K

rpout = 0.025/2 # pipe outer diameter in m

rpin = rpout - 25/11/1000 # pipe internal diameter in m (for SDR11 25mm pipe)

k_pipe = 0.42 # pipe thermal conductivity in W/mK

k_grout = 2.1 # grout thermal conductivity in W/mk - measured EBSS

Lu = (32+25)/1000 # pipe to pipe centre distance in m - measured / designed EBSS

Rg = 1/(4*np.pi*k_grout)*(np.log(rb/rpout) + np.log(rb/Lu) + (k_grout-
k)/(k_grout+k)*np.log(rb**4/(rb**4 - (Lu/2)**4)))

Rp = np.log(rpout/rpin)/(2*np.pi*k_pipe)

Rconv = 1/(2*np.pi*rpin*hconv)

$R_b = R_g + (R_p + R_{conv})/2$

Generating 50x50 shave factors -> 2% interval

alpha = np.linspace(0,1,51)

beta = np.linspace(0,1,51)

Part 2.3

HGSHP system optimisation

def gshp_sizing_individual(a,p1,p2,Tg):

data_alpha = []

data_beta = []

data_q_h_h = []

data_q_h_c = []

data_q_m_h = []

data_q_m_c = []

data_qy = []

data_Ccap = []

data_Ccap_gshp = []

data_Ccap_ghe = []

data_Ccap_rcac = []

data_oc = []

data_oc_gshp = []

data_oc_rcac = []

data_oc_inc = []

data_Egshp = []

data_Ercac = []

data_Etotal = []

data_L = []

data_Lh = []

data_Lc = []

data_subsidy = []

max_demand = max(a['HDv2'].max(),abs(a['HDv2'].min()))

for i in alpha:

for j in beta:

Calculate maximum capacity installed based on the shave factor

a['capacity'] = np.where(a['HDv2']>0,a['HDv2'].max()*i,a['HDv2'].min()*j)

Applying probability of occupancy based on certain hour for building a and b

a['occup1'] = np.where((9 < a['Hour']) & (a['Hour'] <= 18) , p1, p2)

Calculate heating/cooling demand based on probability of occupancy.

Positive value is heating, negative value is cooling

a['HD_build'] = a['HDv2']*a['occup1']

Calculating proportion of energy satisfied by GSHP

```

a['HD_gshp'] = np.where( (abs(a['HDv2']) > abs(a['capacity']))
),a['capacity']*a['occup1'],a['HD_build'])

# Calculating proportion of energy satisfied by auxillary system (RCAC for heating and cooling)
a['HD_boiler'] = np.where( a['HD_build']>0, a['HD_build']-a['HD_gshp'],0)
a['HD_rcac'] = np.where( a['HD_build']<0, a['HD_build']-a['HD_gshp'],0)

# Calculating total energy demand, and proportion of E satisfied by geothermal and RCAC
E_total = a['HD_build'].abs().sum()
E_gshp = a['HD_gshp'].abs().sum()
E_boiler = a['HD_boiler'].sum()
E_rcac = a['HD_rcac'].sum()
E_rcac2 = E_boiler + abs(E_rcac)

# Calculating ground load pulse
# Remember that during heating power consumed by GSHP adds up to heating supplied to
the building
# but during cooling, the power consumed by GSHP also needs to be rejected to the ground
# (ie: ground load > cooling provided)
a['ground_load'] = np.where( a['HD_gshp']>0, a['HD_gshp']/cop_gshp*(cop_gshp-1) ,
a['HD_gshp']/cop_gshp*(cop_gshp+1))
a['gl_h'] = np.where(a['ground_load']>0,a['ground_load'],0)
a['gl_c'] = np.where(a['ground_load']<0,a['ground_load'],0)

# Calculating hourly, monthly and yearly heat pulse
# q_h is the maximum load applied to the ground WITHOUT considering probability of
occupancy (short term); separate peak load between heating and cooling
# q_m is the moving average for a month; separate monthly load between heating and
cooling
# q_y is the yearly average heat pulse applied to the ground
q_h_h = a['HDv2'].max()/cop_gshp*(cop_gshp-1)*i*1000
q_h_c = a['HDv2'].min()/cop_gshp*(cop_gshp+1)*j*1000
q_m_h = a['gl_h'].rolling(30*24).mean().max()*1000
q_m_c = a['gl_c'].rolling(30*24).mean().min()*1000
q_y = (a['ground_load'].mean())*1000

# calculating Tm at peak load. ASSUME flow is 3 GPM/ton
Ti_c = Tg + 20/9*5 # Mean GHE fluid in cooling, 20 F higher than Tg
Ti_h = Tg - 10/9*5 # Mean GHE fluid in cooling, 10 F lower than Tg
To_c = Ti_c - q_h_c/(4.12*32.3/60)/1000
To_h = Ti_h - q_h_h/(4.12*32.3/60)/1000
Tm_c = (Ti_c+To_c)/2
Tm_h = (Ti_h+To_h)/2
#print(To_c,To_h,Tm_c,Tm_h)

# Calculating length of GHE based on ASHRAE method
Lh = (q_h_h*Rb + q_y*R10y + q_m_h*R1m + q_h_h*R6h)/(Tm_h-(Tg+Tp))
Lc = (q_h_c*Rb + q_y*R10y + q_m_c*R1m + q_h_c*R6h)/((Tg+Tp)-Tm_c)
L = max(abs(Lh),abs(Lc))
#print(Lh,Lc, L)

```

calculating capital cost per house

```
Ccap_gshp = max(a['HDv2'].max()*i,abs(a['HDv2'].min()*j) * ic_gshp
Ccap_ghe = L*ic_ghe
Ccap_rcac = max(a['HDv2'].max()*(1-i),abs(a['HDv2'].min()*(1-j)))*ic_rcac*2
#Ccap_rcac = (max_demand-min(a['HDv2'].max()*i,abs(a['HDv2'].min()*j)))*ic_rcac
Ccap = Ccap_gshp + Ccap_ghe + Ccap_rcac
```

calculating yearly operational cost per house

```
oc_gshp = E_gshp/cop_gshp*oc_e
oc_rcac = E_boiler/cop_rcac*oc_e + abs(E_rcac)/cop_rcac*oc_e
oc_inc = - E_gshp*(cop_gshp-1)/cop_gshp*inc
oc = oc_gshp + oc_rcac + oc_inc
subsidy = (E_gshp*(cop_gshp-1)/cop_gshp*inc)
```

results

```
data_alpha.append(i)
data_beta.append(j)
data_q_h_h.append(q_h_h)
data_q_h_c.append(q_h_c)
data_q_m_h.append(q_m_h)
data_q_m_c.append(q_m_c)
data_qy.append(q_y)
data_Ccap_gshp.append(Ccap_gshp)
data_Ccap_ghe.append(Ccap_ghe)
data_Ccap_rcac.append(Ccap_rcac)
data_Ccap.append(Ccap)
data_oc_gshp.append(oc_gshp)
data_oc_rcac.append(oc_rcac)
data_oc_inc.append(oc_inc)
data_oc.append(oc)
data_L.append(L)
data_Lh.append(Lh)
data_Lc.append(Lc)
data_subsidy.append(subsidy)
data_Egshp.append(E_gshp)
data_Ercac.append(E_rcac2)
data_Etotal.append(E_total)
```

```
return pd.DataFrame({'alpha': data_alpha, 'beta': data_beta, 'qh_h':data_q_h_h,
'qh_c':data_q_h_c, 'qm_h':data_q_m_h, 'qm_c':data_q_m_c,'qy':data_qy,
'Ccap_gshp': data_Ccap_gshp,'Ccap_ghe': data_Ccap_ghe,'Ccap_rcac':
data_Ccap_rcac,
'Ccap': data_Ccap, 'oc_gshp': data_oc_gshp, 'oc_rcac':
data_oc_rcac,'oc_inc':data_oc_inc,
'oc':data_oc,'Etotal':data_Etotal,'Egshp':data_Egshp,'E_rcac':data_Ercac ,
'length':data_L,'length_h':data_Lh,'length_c':data_Lc, 'subsidy':data_subsidy})
```

Part 2.4

Calculation for HGSHP system

Constants used for financial analysis

```
ic_gshp = 2000 # installation cost of GSHP ($/kW) => average from Vic Properties
ic_rcac = 1000 # installation cost of RCAC ($/kW)
ic_ghe = 80 # installation cost of GHE ($/m) => average from Vic Properties (include grouting and install)
```

```
cop_gshp = 4 # COP GSHP
cop_rcac = 2.5 # COP RCAC
```

```
T_life = 20 # lifetime of GSHP
DR = 0.035 # discount rate
```

```
inc = 0 # gov incentive for geothermal => the AUD equivalent value of RHI for commercial. Apply 52% of electrical cost
```

Electricity inflation rate

```
r_elec = 0.062
r_gas = 0.0614
real_disc_e = (1+DR)/(1+r_elec)-1
real_disc_g = (1+DR)/(1+r_gas)-1
```

```
def analysis1(b):
```

```
    b['tc'] = b['Ccap'] + -np.pv(real_disc_e, T_life, b['oc'])
    b['TNC'] = b['tc']/(b.Etotal[0]/1000*20)
```

Calculate GHG emission for each alpha beta, per year (emission is in kg CO2e)

```
b['GHG_emitted'] = (b['Egshp']/cop_gshp + b['E_rcac']/cop_rcac)*ghg_elec
b['GHG_saved'] = b['GHG_emitted'][0] - b['GHG_emitted']
```

Calculate MAC

```
b['mc'] = b['tc'] - b['tc'][0]
b['mac'] = b.mc/(b.GHG_saved*T_life/1000)
```

Calculate lifetime emission per NPV

```
b['aa'] = b['GHG_saved']*20/b['tc']
```

Calculate payback period

```
b['payback'] = -(b['Ccap']-b['Ccap'][0])/(b['oc']-b['oc'][0])
```

Example calculation for Sydney, base case scenario: 1e,80d

```
ic_ghe = 80
oc_e = 0.238
ghg_elec = 0.83
```

```
house_sydney_1e80d = gshp_sizing_individual(sydney.weather,1,1,sydney.tg)
analysis1(house_sydney_1e80d)
```

Part 3 – HGSHP system analysis code, environmental analysis

Part 3.1

Calculate lifetime emission (initial + operational)

for HGSHP1

```
lambdafunc = lambda x: pd.Series([(x['length']*7.8 + x['Ccap_gshp']/2000*69*1 +  
x['Ccap_rcac']/2000*69*2)/1000,  
                                (x['GHG_emitted']*20/1000 ),  
                                ((x['length']*7.8 + x['Ccap_gshp']/2000*69*1 + x['Ccap_rcac']/2000*69*2)/1000 +  
x['GHG_emitted']*20/1000)])
```

for HGSHP2

```
lambdafunc2 = lambda x: pd.Series([(x['length']*7.8 + x['Ccap_gshp']/2000*69*1 +  
x['Ccap_gas']/1000*1.4*2 + x['Ccap_rcac']/2000*69*2)/1000,  
                                (x['GHG_emitted']*20/1000 ),  
                                ((x['length']*7.8 + x['Ccap_gshp']/2000*69*1 + x['Ccap_gas']/1000*1.4*2 +  
x['Ccap_rcac']/2000*69*2)/1000 + x['GHG_emitted']*20/1000)])
```

calculate emissions for 20 yrs in ton co2e Adelaide / RUN THE CODE

```
a_rcac_1e80d[['GHG_init','GHG_op','GHG_lge']] = a_rcac_1e80d.apply(lambdafunc, axis = 1)  
a_gas_1e1g80d[['GHG_init','GHG_op','GHG_lge']] = a_gas_1e1g80d.apply(lambdafunc2, axis = 1)
```

Part 3.2

Calculate Pareto Optimum

```
def pareto_frontier(Xs, Ys, maxX = True, maxY = True):
```

```
    # Sort the list in either ascending or descending order of X
```

```
    myList = sorted([[Xs[i], Ys[i]] for i in range(len(Xs))], reverse=maxX)
```

```
    # Start the Pareto frontier with the first value in the sorted list
```

```
    p_front = [myList[0]]
```

```
    # Loop through the sorted list
```

```
    for pair in myList[1:]:
```

```
        if maxY:
```

```
            if pair[1] >= p_front[-1][1]: # Look for higher values of Y...
```

```
                p_front.append(pair) # ... and add them to the Pareto frontier
```

```
        else:
```

```
            if pair[1] <= p_front[-1][1]: # Look for lower values of Y...
```

```
                p_front.append(pair) # ... and add them to the Pareto frontier
```

```
    # Turn resulting pairs back into a list of Xs and Ys
```

```
    p_frontX = [pair[0] for pair in p_front]
```

```
    p_frontY = [pair[1] for pair in p_front]
```

```
    return p_frontX, p_frontY
```

Calculate kneedle. Kneedle is the elbow of the curve

```
class kneedle:
    def __init__(self,pareto):

        #get coordinates of all the points
        self.pareto = pareto

        #####
        # For HGSH1
        allCoord = np.vstack((self.pareto.p_front1[0],self.pareto.p_front1[1])).T

        # get the first point
        firstPoint = allCoord[0]

        # get vector between first and last point - this is the line
        lineVec = allCoord[-1] - allCoord[0]
        lineVecNorm = lineVec / np.sqrt(np.sum(lineVec**2))

        # find the distance from each point to the line:
        # vector between all points and first point
        vecFromFirst = allCoord - firstPoint

        nPoints = len(allCoord)
        scalarProduct = np.sum(vecFromFirst * np.matlib.repmat(lineVecNorm, nPoints, 1), axis=1)
        vecFromFirstParallel = np.outer(scalarProduct, lineVecNorm)
        vecToLine = vecFromFirst - vecFromFirstParallel

        # distance to line is the norm of vecToLine
        distToLine = np.sqrt(np.sum(vecToLine ** 2, axis=1))

        # knee/elbow is the point with max distance value
        idxOfBestPoint = np.argmax(distToLine)

        # find the kneedle pt
        self.k1 = allCoord[idxOfBestPoint]

        #####
        # For HGSH2
        allCoord = np.vstack((self.pareto.p_front2[0],self.pareto.p_front2[1])).T

        # get the first point
        firstPoint = allCoord[0]

        # get vector between first and last point - this is the line
        lineVec = allCoord[-1] - allCoord[0]
        lineVecNorm = lineVec / np.sqrt(np.sum(lineVec**2))

        # find the distance from each point to the line:
        # vector between all points and first point
        vecFromFirst = allCoord - firstPoint
```

```

nPoints = len(allCoord)
scalarProduct = np.sum(vecFromFirst * np.matlib.repmat(lineVecNorm, nPoints, 1), axis=1)
vecFromFirstParallel = np.outer(scalarProduct, lineVecNorm)
vecToLine = vecFromFirst - vecFromFirstParallel

```

```

# distance to line is the norm of vecToLine

```

```

distToLine = np.sqrt(np.sum(vecToLine ** 2, axis=1))

```

```

# knee/elbow is the point with max distance value

```

```

idxOfBestPoint = np.argmax(distToLine)

```

```

# find the kneedle pt

```

```

self.k2 = allCoord[idxOfBestPoint]

```

```

# Calculate the optimum points of pareto curve

```

```

class pareto:

```

```

    def __init__(self, houses1, houses2):

```

```

        # calculate pareto optimum 1

```

```

        self.houses1 = houses1

```

```

        self.Xs1, self.Ys1 = self.houses1.tc, self.houses1.GHG_lge

```

```

        self.p_front1 = pareto_frontier(self.Xs1, self.Ys1, maxX = False, maxY = False)

```

```

        self.a1 = self.houses1.loc[self.houses1['TNC'].idxmin()].alpha

```

```

        self.b1 = self.houses1.loc[self.houses1['TNC'].idxmin()].beta

```

```

        self.c1 = self.houses1.loc[self.houses1['TNC'].idxmin()].TNC

```

```

        self.d1 = self.houses1.loc[self.houses1['TNC'].idxmin()].tc

```

```

        self.e1 = self.houses1.loc[self.houses1['TNC'].idxmin()].GHG_lge

```

```

        self.f1 = self.houses1.loc[self.houses1['GHG_lge'].idxmin()].alpha

```

```

        self.g1 = self.houses1.loc[self.houses1['GHG_lge'].idxmin()].beta

```

```

        # calculate pareto optimum 2

```

```

        self.houses2 = houses2

```

```

        self.Xs2, self.Ys2 = self.houses2.tc, self.houses2.GHG_lge

```

```

        self.p_front2 = pareto_frontier(self.Xs2, self.Ys2, maxX = False, maxY = False)

```

```

        self.a2 = self.houses2.loc[self.houses2['TNC'].idxmin()].alpha

```

```

        self.b2 = self.houses2.loc[self.houses2['TNC'].idxmin()].beta

```

```

        self.c2 = self.houses2.loc[self.houses2['TNC'].idxmin()].TNC

```

```

        self.d2 = self.houses2.loc[self.houses2['TNC'].idxmin()].tc

```

```

        self.e2 = self.houses2.loc[self.houses2['TNC'].idxmin()].GHG_lge

```

```

        self.f2 = self.houses2.loc[self.houses2['GHG_lge'].idxmin()].alpha

```

```

        self.g2 = self.houses2.loc[self.houses2['GHG_lge'].idxmin()].beta

```

```

        # -----

```

```
# -----
```

```
# Apply kneedle algorithm
```

```
self.k = kneedle(self)
```

```
# -----
```

```
# -----
```

```
# Find corresponding shave factor for pareto optimum
```

```
self.aa = self.houses1.loc[:,['alpha','beta','tc','GHG_lge']]
```

```
self.bb = self.aa[self.aa['tc'].isin(self.p_front1[0])]
```

```
self.cc = self.houses2.loc[:,['alpha','beta','tc','GHG_lge']]
```

```
self.dd = self.cc[self.cc['tc'].isin(self.p_front2[0])]
```

```
# find shave factors for kneedle point
```

```
self.aa = self.bb[self.bb['tc'] == self.k.k1[0]].alpha
```

```
self.bb = self.bb[self.bb['tc'] == self.k.k1[0]].beta
```

```
self.cc = self.dd[self.dd['tc'] == self.k.k2[0]].alpha
```

```
self.dd = self.dd[self.dd['tc'] == self.k.k2[0]].beta
```

```
# -----
```

```
# RUN THE CODE
```

```
PRTa_1e80d = pareto(a_rcac_1e80d,a_gas_1e1g80d)
```

Sample Python codes used for DGSHP system analysis (Chapter 7)

Examples are given for district with combination of 4 energy load

generate permutation

```
desired_result = by_size(combs,4)
print(len(desired_result))
# -----
choice_indices = np.random.choice(len(desired_result), 715, replace=False)
choices = [desired_result[a] for a in choice_indices]
print(len(choices))
```

generate district

```
d4={}

for a in choices:
    i = a[0]
    j = a[1]
    k = a[2]
    l = a[3]
    name = str(i)+str(j)+str(k)+str(l)
    new_df = pd.concat([district, (indiv[i-1]['HDv2']+indiv[j-1]['HDv2']+indiv[k-1]['HDv2']+indiv[l-1]['HDv2']).rename('HDv2')], axis=1)
    new_df2 = gshp_sizing_individual(new_df,1,1,melb.tg)
    new_df2['house1'] = i
    new_df2['house2'] = j
    new_df2['house3'] = k
    new_df2['house4'] = l
    new_df2['Etotal2'] = (indiv[i-1].HDv2[indiv[i-1].HDv2 >0].sum()+abs(indiv[i-1].HDv2[indiv[i-1].HDv2 <0].sum()))\
        +(indiv[j-1].HDv2[indiv[j-1].HDv2 >0].sum()+abs(indiv[j-1].HDv2[indiv[j-1].HDv2 <0].sum()))\
        +(indiv[k-1].HDv2[indiv[k-1].HDv2 >0].sum()+abs(indiv[k-1].HDv2[indiv[k-1].HDv2 <0].sum()))\
        +(indiv[l-1].HDv2[indiv[l-1].HDv2 >0].sum()+abs(indiv[l-1].HDv2[indiv[l-1].HDv2 <0].sum()))
    analysis2(new_df2)
    d4["district{0}".format(name)] = new_df2
```

```
# generate district 2
```

```
district_comb4 = []  
district_comb4_lowTNC = []  
district_comb4_lowGHG = []  
district_comb4_lowtc = []  
indiv_comb4_lowTNC = []  
indiv_comb4_lowGHG = []  
indiv_comb4_lowtc = []
```

```
for key, value in d4.items():
```

```
    #print(key,key[-2])  
    district_comb4.append(key)  
    district_comb4_lowTNC.append(value.TNC.min())  
    indiv_comb4_lowTNC.append((indiv_TNC[value.house1[0]-1]+indiv_TNC[value.house2[0]-1]+indiv_TNC[value.house3[0]-1]+indiv_TNC[value.house4[0]-1])/4 )  
    district_comb4_lowGHG.append(value.GHG_emitted.min())  
    indiv_comb4_lowGHG.append((indiv_GHG_emitted[value.house1[0]-1]+indiv_GHG_emitted[value.house2[0]-1]+indiv_GHG_emitted[value.house3[0]-1]+indiv_GHG_emitted[value.house4[0]-1] )  
    district_comb4_lowtc.append(value.tc.min())  
    indiv_comb4_lowtc.append((indiv_tc[value.house1[0]-1]+indiv_tc[value.house2[0]-1]+indiv_tc[value.house3[0]-1]+indiv_tc[value.house4[0]-1] )  
    #print(key, value.TNC.min(), (indiv_TNC[value.house1[0]-1]+indiv_TNC[value.house2[0]-1])/2 )
```

```
df_district4 = pd.DataFrame({'district_TNC':district_comb4_lowTNC,  
'indiv_TNC':indiv_comb4_lowTNC,  
    'district_GHG':district_comb4_lowGHG, 'indiv_GHG':indiv_comb4_lowGHG,  
    'district_tc':district_comb4_lowtc, 'indiv_tc':indiv_comb4_lowtc,  
    }, index = district_comb4 )
```

```
df_district4['TNC_ratio'] = df_district4.district_TNC/df_district4.indiv_TNC  
df_district4['GHG_ratio'] = df_district4.district_GHG/df_district4.indiv_GHG  
df_district4['tc_ratio'] = df_district4.district_tc/df_district4.indiv_tc
```

Appendix D

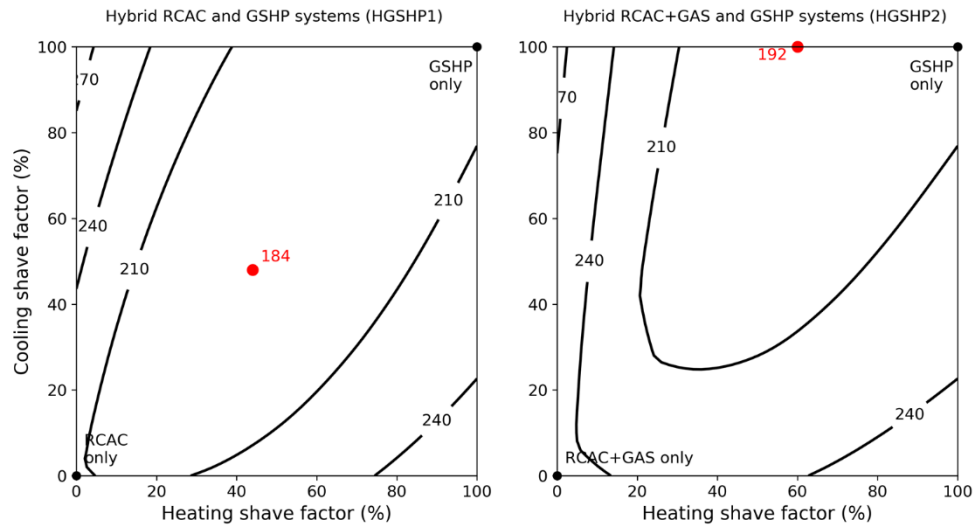
Additional results from Chapter 5 and Chapter 6

Additional results from Chapter 5

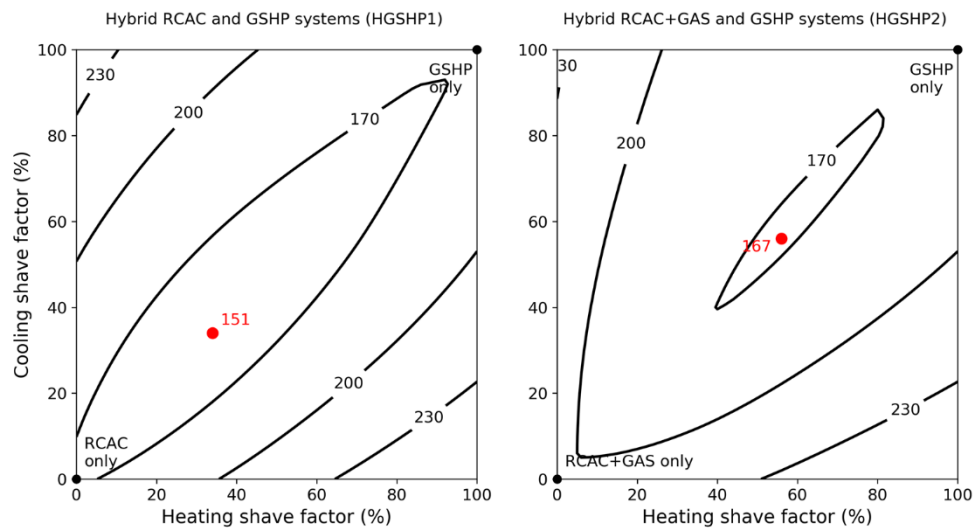
Part 1 – TNC contour plot for all base cases from the other 7 cities investigated in Chapter 5

Note: Results for Cairns, Hobart and Sydney are presented in Chapter 5

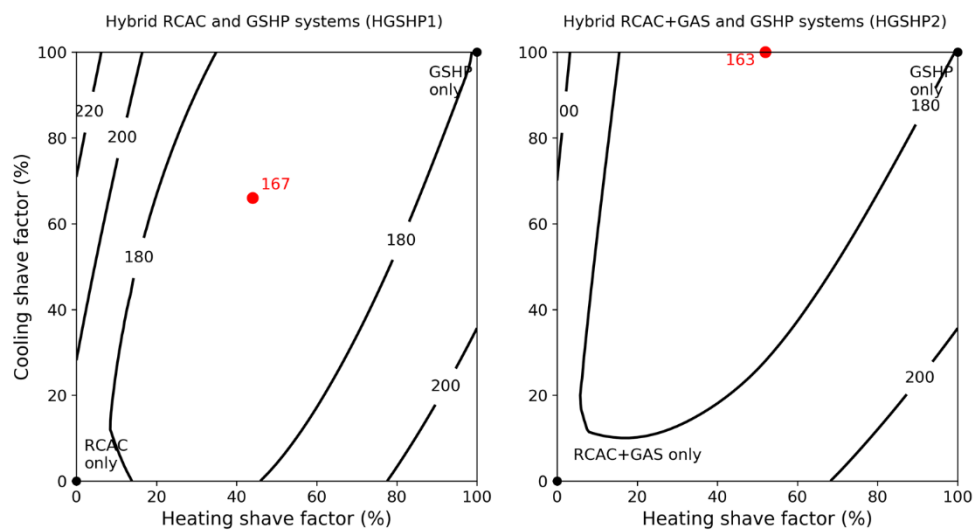
Adelaide



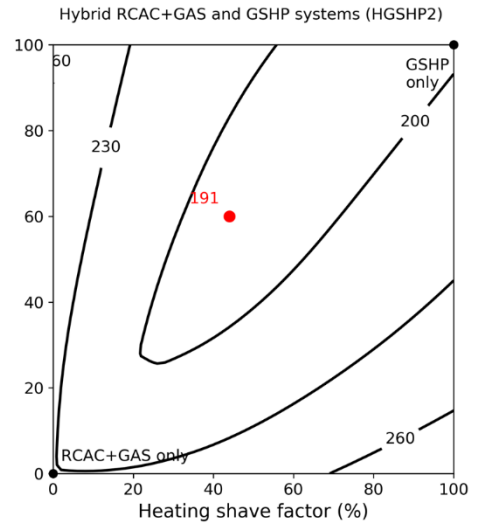
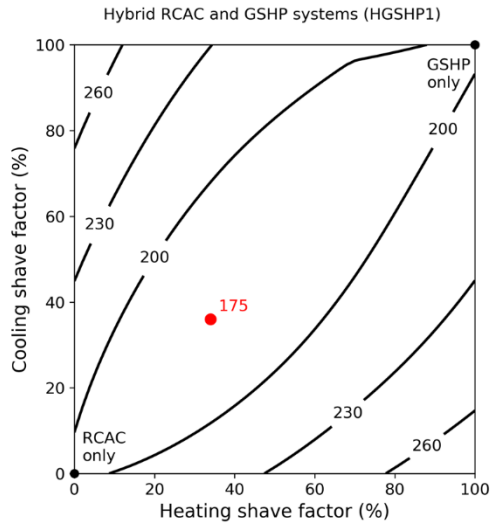
Brisbane



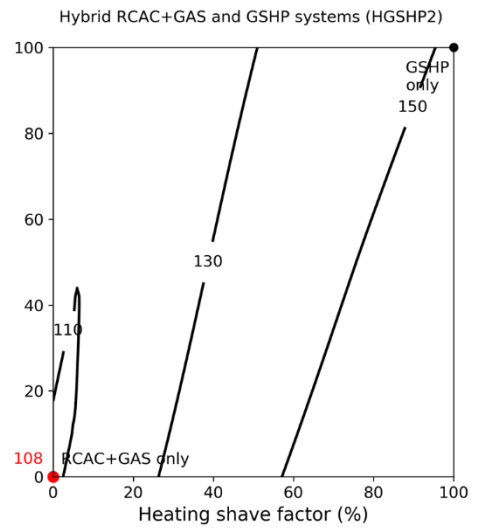
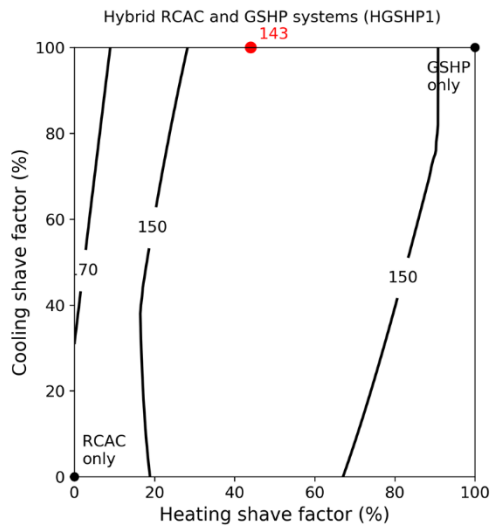
Melbourne



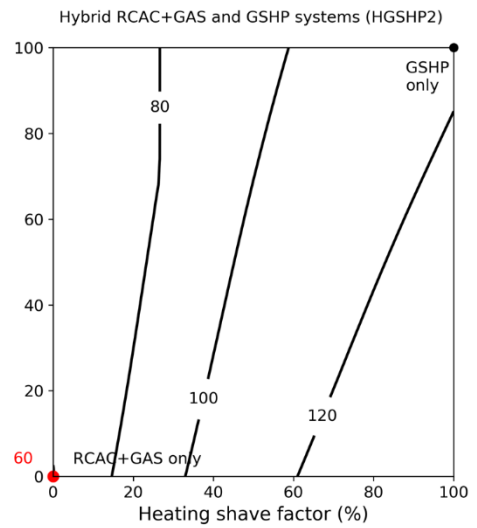
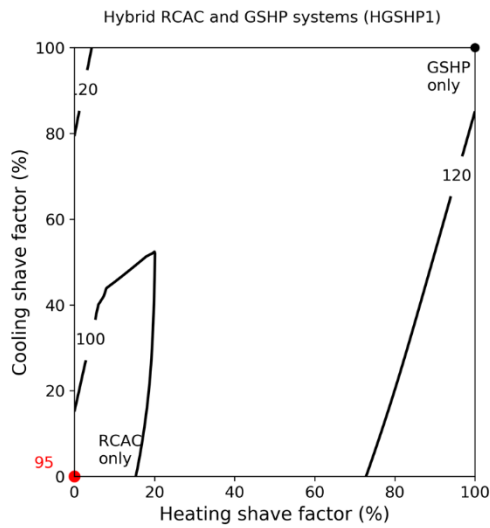
Perth



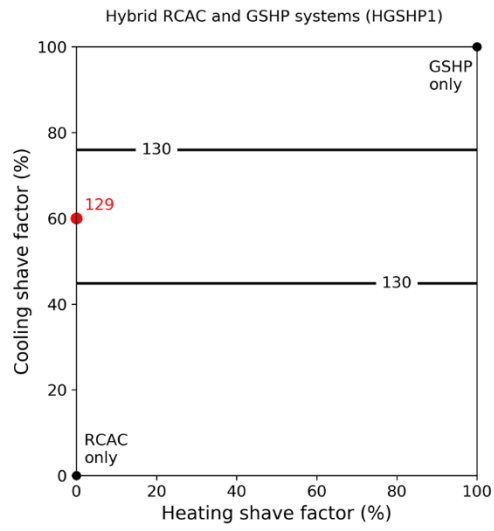
London



Montreal



Singapore



Part 2 – Tabulated values for all scenario

Base case scenario

Location	Category	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Adelaide	RCAC system	0	0	213.4	0
	RCAC+gas system	0	0	252.8	0
	GSHP system	1	1	200	243.8
	HGSHP1 system	0.44	0.48	184.5	148
	HGSHP2 system	0.6	1	192.2	182.8
Brisbane	RCAC system	0	0	165.4	0
	RCAC+gas system	0	0	208.9	0
	GSHP system	1	1	172.8	194.9
	HGSHP1 system	0.34	0.34	151.5	84
	HGSHP2 system	0.56	0.56	167.2	126.2
Cairns	RCAC system	0	0	156.9	0
	RCAC+gas system	N/A			
	GSHP system	1	1	159	275.9
	HGSHP1 system	1	0.38	147.9	152
	HGSHP2 system	N/A			
Hobart	RCAC system	0	0	147.6	0
	RCAC+gas system	0	0	230	0
	GSHP system	1	1	160.5	298.4
	HGSHP1 system	0.24	0.36	143.9	119
	HGSHP2 system	0.64	1	146.1	241.6
Melbourne	RCAC system	0	0	187.6	0
	RCAC+gas system	0	0	187.1	0
	GSHP system	1	1	180.3	292.4
	HGSHP1 system	0.44	0.66	167.4	183
	HGSHP2 system	0.52	1	163.2	206
Perth	RCAC system	0	0	196.1	0
	RCAC+gas system	0	0	231.8	0
	GSHP system	1	1	198.3	227.1
	HGSHP1 system	0.34	0.36	175	106
	HGSHP2 system	0.44	0.6	191	129.4
Sydney	RCAC system	0	0	182.9	0
	RCAC+gas system	0	0	242.2	0
	GSHP system	1	1	189.7	181.2
	HGSHP1 system	0.32	0.32	168	76
	HGSHP2 system	0.6	0.6	185	127.4
London	RCAC system	0	0	161.2	0
	RCAC+gas system	0	0	107.7	0
	GSHP system	1	1	151.7	401.2
	HGSHP1 system	0.44	1	143.3	269
	HGSHP2 system	0	0	107.7	0
Montreal	RCAC system	0	0	94.7	0
	RCAC+gas system	0	0	59.5	0
	GSHP system	1	1	117.4	589.9
	HGSHP1 system	0	0	94.7	0
	HGSHP2 system	0	0	59.5	0
Singapore	RCAC system	0	0	137.8	0
	RCAC+gas system	N/A			
	GSHP system	1	1	132.8	325.7
	HGSHP1 system	0	0.6	129.3	257
	HGSHP2 system	N/A			

Effect of changes in drilling costs

Location	Category	Drilling costs (\$/m)	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Adelaide	HGSHP1 system	50	0.56	0.62	169.1	175
		80	0.44	0.48	184.5	148
		100	0.36	0.4	193.2	126
		150	0.14	0.2	208.7	55
	HGSHP2 system	50	0.9	1	172.4	230.3
		80	0.6	1	192.2	182.8
		100	0.52	1	203.3	166
		150	0.3	0.66	224.8	106.9
Brisbane	HGSHP1 system	50	0.48	0.48	140.6	112
		80	0.34	0.34	151.5	84
		100	0.26	0.26	157	67
		150	0.06	0.06	164.7	17
	HGSHP2 system	50	1	1	151.2	194.9
		80	0.56	0.56	167.2	126.2
		100	0.5	0.5	176.2	115.7
		150	0.3	0.3	193.7	75.6
Cairns	HGSHP1 system	50	1	0.56	135.7	202
		80	1	0.38	147.9	152
		100	0.64	0.24	153.6	103
		150	0	0	156.9	0
	HGSHP2 system	N/A				
Hobart	HGSHP1 system	50	0.46	0.7	132.6	197
		80	0.24	0.36	143.9	119
		100	0.04	0.06	147.5	22
		150	0	0	147.6	0
	HGSHP2 system	50	0.66	1	128.8	245.6
		80	0.64	1	146.1	241.6
		100	0.64	1	157.4	241.6
		150	0.52	1	184.6	213.8
Melbourne	HGSHP1 system	50	0.56	0.84	152.6	216
		80	0.44	0.66	167.4	183
		100	0.32	0.48	175.7	144
		150	0	0	187.6	0
	HGSHP2 system	50	0.66	1	146.1	238.8
		80	0.52	1	163.2	206
		100	0.36	1	172.4	157.1
		150	0.12	0.42	183.7	56.9
Perth	HGSHP1 system	50	0.44	0.46	162.4	130
		80	0.34	0.36	175	106
		100	0.24	0.28	181.6	78
		150	0.14	0.18	191.8	47
	HGSHP2 system	50	1	1	174.2	227.1
		80	0.44	0.6	191	129.4
		100	0.4	0.54	199.7	119.9
		150	0.26	0.34	217	83

Location	Category	Drilling costs (\$/m)	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Sydney	HGSHP1 system	50	0.46	0.46	156.4	103
		80	0.32	0.32	168	76
		100	0.24	0.24	173.7	60
		150	0.06	0.06	182.1	16
	HGSHP2 system	50	0.88	0.9	166.8	166.7
		80	0.6	0.6	185	127.4
		100	0.52	0.52	195.2	113.7
		150	0.36	0.36	216.3	84.4
London	HGSHP1 system	50	0.58	1	129	319
		80	0.44	1	143.3	269
		100	0.34	0.82	151.1	223
		150	0	0	161.2	0
	HGSHP2 system	50	0.04	0.26	107.5	29.7
		80	0	0	107.7	0
		100	0	0	107.7	0
		150	0	0	107.7	0
Montreal	HGSHP1 system	0.2	0.52	92.7	234	0.2
		0	0	94.7	0	0
		0	0	94.7	0	0
		0	0	94.7	0	0
	HGSHP2 system	0	0	59.5	0	0
		0	0	59.5	0	0
		0	0	59.5	0	0
		0	0	59.5	0	0
Singapore	HGSHP1 system	0	0.72	119.1	286	0
		0	0.6	129.3	257	0
		0	0.44	135.1	205	0
		0	0	137.8	0	0
	HGSHP2 system				N/A	

Effect of changes in energy prices

Note:

- 1e1g means current electricity and gas prices.
- 1e2g means current electricity but with double the current gas prices
- 2e1g means double the current electricity with the current gas prices
- 2e2g means double both the current electricity and gas prices

Location	Category	Energy prices	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Adelaide	HGSHP1 system	1e	0.44	0.48	184.5	148
		2e	0.58	0.64	279.3	179
	HGSHP2 system	1e1g	0.6	1	192.2	183
		1e2g	0.78	1	193.9	213
		2e1g	0.24	0.52	269.1	88
		2e2g	0.74	1	283.6	207
Brisbane	HGSHP1 system	1e	0.34	0.34	151.5	84
		2e	0.54	0.54	219.2	123
	HGSHP2 system	1e1g	0.56	0.56	167.2	126
		1e2g	0.68	0.7	168.9	147
		2e1g	0.58	0.58	229.9	130
		2e2g	0.68	0.7	231.1	147
Cairns	HGSHP1 system	1e	1	0.38	147.9	152
		2e	1	0.62	221.8	216
	HGSHP2 system	N/A				
Hobart	HGSHP1 system	1e	0.24	0.36	143.9	119
		2e	0.52	0.8	214.9	214
	HGSHP2 system	1e1g	0.64	1	146.1	242
		1e2g	0.7	1	149.8	253
		2e1g	0.58	1	208	228
		2e2g	0.66	1	212.4	246
Melbourne	HGSHP1 system	1e	0.44	0.66	167.4	183
		2e	0.6	0.9	253	226
	HGSHP2 system	1e1g	0.52	1	163.2	206
		1e2g	0.66	1	166.4	239
		2e1g	0	0.08	201.6	14
		2e2g	0.66	1	246.1	239
Perth	HGSHP1 system	1e	0.34	0.36	175	106
		2e	0.48	0.5	257.8	139
	HGSHP2 system	1e1g	0.44	0.6	191	129
		1e2g	0.62	0.86	194.1	167
		2e1g	0.3	0.4	262.4	95
		2e2g	0.58	0.8	270	159
Sydney	HGSHP1 system	1e	0.32	0.32	168	76
		2e	0.52	0.52	242	114
	HGSHP2 system	1e1g	0.6	0.6	185	127
		1e2g	0.74	0.76	186.8	148
		2e1g	0.56	0.56	251.2	121
		2e2g	0.72	0.74	253.7	146

Location	Category	Energy prices	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
London	HGSHP1 system	1e	0.44	1	143.3	269
		2e	0.64	1	210.3	335
	HGSHP2 system	1e1g	0	0	107.7	0
		1e2g	0.44	1	135.9	269
		2e1g	0	0	110	0
2e2g		0.04	0.26	180.9	30	
Montreal	HGSHP1 system	1e	0	0	94.7	0
		2e	0.36	0.94	133.3	373
	HGSHP2 system	1e1g	0	0	59.5	0
		1e2g	0	0	77	0
		2e1g	0	0	61.5	0
2e2g		0	0	79	0	
Singapore	HGSHP1 system	1e	0	0.6	129.3	257
		2e	0	0.76	208.4	293
	HGSHP2 system				N/A	

Effect of changes in ground thermal conductivity

Location	Category	Thermal conductivity (W/m.K)	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Adelaide	HGSHP1 system	2.5	0.44	0.48	184.5	148
		2.0	0.38	0.42	190	153
		1.5	0.32	0.36	198.2	162
		1.0	0.1	0.2	208.9	72
		0.7	0.06	0.12	212	52
	HGSHP2 system	2.5	0.6	1	192.2	183
		2.0	0.56	1	199	201
		1.5	0.48	1	209.3	219
		1.0	0.28	0.74	224.8	189
		0.7	0.22	0.56	233.9	185
Brisbane	HGSHP1 system	2.5	0.34	0.34	151.5	84
		2.0	0.3	0.3	155	87
		1.5	0.22	0.22	159.6	80
		1.0	0.06	0.06	164.7	31
		0.7	0	0	165.4	0
	HGSHP2 system	2.5	0.56	0.56	167.2	126
		2.0	0.54	0.54	172.4	140
		1.5	0.46	0.44	180.1	144
		1.0	0.36	0.32	191.7	146
		0.7	0.3	0.26	199.4	148
Cairns	HGSHP1 system	2.5	1	0.38	147.9	152
		2.0	0.8	0.3	152.1	147
		1.5	0.26	0.1	156.3	66
		1.0	0	0	156.9	0
		0.7	0	0	156.9	0
	HGSHP2 system	N/A				
Hobart	HGSHP1 system	2.5	0.24	0.36	143.9	119
		2.0	0.12	0.18	146.9	74
		1.5	0	0	147.6	0
		1.0	0	0	147.6	0
		0.7	0	0	147.6	0
	HGSHP2 system	2.5	0.64	1	146.1	242
		2.0	0.64	1	153.3	280
		1.5	0.64	1	165	342
		1.0	0.56	1	186.9	431
		0.7	0.44	1	204.2	459
Melbourne	HGSHP1 system	2.5	0.44	0.66	167.4	183
		2.0	0.36	0.54	173.1	184
		1.5	0.24	0.36	180.7	162
		1.0	0.02	0.06	187.5	19
		0.7	0	0	187.6	0
	HGSHP2 system	2.5	0.52	1	163.2	206
		2.0	0.44	1	169.5	213
		1.5	0.2	0.88	176.8	134
		1.0	0.12	0.5	183.7	109
		0.7	0.06	0.24	186.5	66

Location	Category	Thermal conductivity (W/m.K)	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Perth	HGSHP1 system	2.5	0.34	0.36	175	106
		2.0	0.28	0.32	179	102
		1.5	0.22	0.26	184.1	99
		1.0	0.14	0.18	190.6	84
		0.7	0.08	0.1	194.6	60
	HGSHP2 system	2.5	0.44	0.6	191	129
		2.0	0.4	0.54	195.9	136
		1.5	0.38	0.52	203	156
		1.0	0.3	0.4	214.5	166
		0.7	0.2	0.26	222.2	140
Sydney	HGSHP1 system	2.5	0.32	0.32	168	76
		2.0	0.28	0.28	171.4	78
		1.5	0.22	0.22	176.2	76
		1.0	0.08	0.08	181.9	39
		0.7	0	0	182.9	0
	HGSHP2 system	2.5	0.6	0.6	185	127
		2.0	0.56	0.56	190.5	137
		1.5	0.52	0.52	198.8	153
		1.0	0.4	0.38	212.9	161
		0.7	0.32	0.3	222.4	159
London	HGSHP1 system	2.5	0.44	1	143.3	269
		2.0	0.38	0.92	148.9	284
		1.5	0.24	0.58	156.4	244
		1.0	0	0	161.2	0
		0.7	0	0	161.2	0
	HGSHP2 system	2.5	0	0	107.7	0
		2.0	0	0	107.7	0
		1.5	0	0	107.7	0
		1.0	0	0	107.7	0
		0.7	0	0	107.7	0
Montreal	HGSHP1 system	2.5	0	0	94.7	0
		2.0	0	0	94.7	0
		1.5	0	0	94.7	0
		1.0	0	0	94.7	0
		0.7	0	0	94.7	0
	HGSHP2 system	2.5	0	0	59.5	0
		2.0	0	0	59.5	0
		1.5	0	0	59.5	0
		1.0	0	0	59.5	0
		0.7	0	0	59.5	0
Singapore	HGSHP1 system	2.5	0	0.6	129.3	257
		2.0	0	0.52	133.6	274
		1.5	0	0	137.8	0
		1.0	0	0	137.8	0
		0.7	0	0	137.8	0
	HGSHP2 system	N/A				

Effect of changes in CoPs of RCAC

Location	Category	CoPs of RCAC	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)	
Adelaide	HGSHP1 system	+ 0.5	0.26	0.28	178.9	97	
		Base case	0.44	0.48	184.5	148	
		- 0.5	0.56	0.62	187.7	175	
	HGSHP2 system	+ 0.5	0.6	1	192.2	183	
		Base case	0.6	1	192.2	183	
		- 0.5	0.6	1	192.2	183	
Brisbane	HGSHP1 system	+ 0.5	0.16	0.16	145.2	43	
		Base case	0.34	0.34	151.5	84	
		- 0.5	0.48	0.48	155.4	112	
	HGSHP2 system	+ 0.5	0.54	0.54	166.5	123	
		Base case	0.56	0.56	167.2	126	
		- 0.5	0.6	0.6	168	133	
Cairns	HGSHP1 system	+ 0.5	0	0	137.4	0	
		Base case	1	0.38	147.9	152	
		- 0.5	1	0.56	151.4	202	
	HGSHP2 system	N/A					
	Hobart	HGSHP1 system	+ 0.5	0	0	129.7	0
			Base case	0.24	0.36	143.9	119
- 0.5			0.46	0.7	149.6	197	
HGSHP2 system		+ 0.5	0.64	1	146.1	242	
		Base case	0.64	1	146.1	242	
		- 0.5	0.64	1	146.1	242	
Melbourne	HGSHP1 system	+ 0.5	0.2	0.3	160.9	96	
		Base case	0.44	0.66	167.4	183	
		- 0.5	0.56	0.84	170.5	216	
	HGSHP2 system	+ 0.5	0.52	1	163.2	206	
		Base case	0.52	1	163.2	206	
		- 0.5	0.52	1	163.2	206	
Perth	HGSHP1 system	+ 0.5	0.16	0.2	168.4	54	
		Base case	0.34	0.36	175	106	
		- 0.5	0.44	0.46	179	130	
	HGSHP2 system	+ 0.5	0.44	0.6	190.8	129	
		Base case	0.44	0.6	191	129	
		- 0.5	0.48	0.66	191.3	138	
Sydney	HGSHP1 system	+ 0.5	0.16	0.16	161	41	
		Base case	0.32	0.32	168	76	
		- 0.5	0.46	0.46	172.6	103	
	HGSHP2 system	+ 0.5	0.58	0.58	184.7	124	
		Base case	0.6	0.6	185	127	
		- 0.5	0.66	0.68	185.3	137	
London	HGSHP1 system	+ 0.5	0.2	0.48	137.4	142	
		Base case	0.44	1	143.3	269	
		- 0.5	0.58	1	145.9	319	
	HGSHP2 system	+ 0.5	0	0	107.3	0	
		Base case	0	0	107.7	0	
		- 0.5	0	0	108.3	0	

Location	Category	CoPs of RCAC	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Montreal	HGSHP1 system	+ 0.5	0	0	84.9	0
		Base case	0	0	94.7	0
		- 0.5	0.22	0.56	107.5	254
	HGSHP2 system	+ 0.5	0	0	59.1	0
		Base case	0	0	59.5	0
		- 0.5	0	0	60.2	0
Singapore	HGSHP1 system	+ 0.5	0	0	117.2	0
		Base case	0	0.6	129.3	257
		- 0.5	0	0.74	130.4	289
	HGSHP2 system	N/A				

Effect of changes in CoPs of GSHP

Location	Category	CoPs of GSHP	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Adelaide	HGSHP1 system	+ 0.5	0.46	0.5	177.7	157
		Base case	0.44	0.48	184.5	148
		- 0.5	0.38	0.42	192.6	127
	HGSHP2 system	+ 0.5	0.62	1	184.8	192
		Base case	0.6	1	192.2	183
		- 0.5	0.58	1	201.3	173
Brisbane	HGSHP1 system	+ 0.5	0.36	0.36	147.1	90
		Base case	0.34	0.34	151.5	84
		- 0.5	0.28	0.28	157.4	73
	HGSHP2 system	+ 0.5	0.56	0.6	162.1	130
		Base case	0.56	0.56	167.2	126
		- 0.5	0.56	0.56	175	129
Cairns	HGSHP1 system	+ 0.5	1	0.46	141.2	173
		Base case	1	0.38	147.9	152
		- 0.5	0.58	0.22	154.7	98
	HGSHP2 system	N/A				
Hobart	HGSHP1 system	+ 0.5	0.3	0.46	140.3	147
		Base case	0.24	0.36	143.9	119
		- 0.5	0.08	0.12	147.2	41
	HGSHP2 system	+ 0.5	0.64	1	140.8	249
		Base case	0.64	1	146.1	242
		- 0.5	0.64	1	152.8	233
Melbourne	HGSHP1 system	+ 0.5	0.48	0.72	161.2	200
		Base case	0.44	0.66	167.4	183
		- 0.5	0.36	0.54	174.8	152
	HGSHP2 system	+ 0.5	0.56	1	156.6	222
		Base case	0.52	1	163.2	206
		- 0.5	0.48	1	171.1	188
Perth	HGSHP1 system	+ 0.5	0.36	0.38	169.8	115
		Base case	0.34	0.36	175	106
		- 0.5	0.3	0.32	181.2	92
	HGSHP2 system	+ 0.5	0.44	0.64	185	133
		Base case	0.44	0.6	191	129
		- 0.5	0.46	0.58	198.5	129
Sydney	HGSHP1 system	+ 0.5	0.36	0.38	163.2	87
		Base case	0.32	0.32	168	76
		- 0.5	0.26	0.24	173.3	61
	HGSHP2 system	+ 0.5	0.6	0.64	179.7	131
		Base case	0.6	0.6	185	127
		- 0.5	0.62	0.58	191.4	126
London	HGSHP1 system	+ 0.5	0.48	1	138.6	292
		Base case	0.44	1	143.3	269
		- 0.5	0.38	0.92	148.9	234
	HGSHP2 system	+ 0.5	0	0	107.7	0
		Base case	0	0	107.7	0
		- 0.5	0	0	107.7	0

Location	Category	CoPs of GSHP	Alpha	Beta	Lowest TNC (\$/MWh)	GHE Length (m)
Montreal	HGSHP1 system	+ 0.5	0	0	94.7	0
		Base case	0	0	94.7	0
		- 0.5	0	0	94.7	0
	HGSHP2 system	+ 0.5	0	0	59.5	0
		Base case	0	0	59.5	0
		- 0.5	0	0	59.5	0
Singapore	HGSHP1 system	+ 0.5	0	0.68	119.2	270
		Base case	0	0.6	129.3	257
		- 0.5	0	0	137.8	0
	HGSHP2 system				N/A	

Additional results from Chapter 6

Base case scenario

Min NPC = minimum NPC scenario, EW = equal weight scenario, Min LGE = minimum lifetime emission scenario

Location	Category	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Adelaide	HGSHP1 system	Min NPC	0.44	0.48	57,644	38.6	148
		EW	0.6	0.66	58,365	36.3	183
		Min LGE	0.84	0.92	60,782	35.6	222
	HGSHP2 system	Min NPC	0.6	1	60,047	36	183
		EW	0.7	1	60,160	35.6	201
		Min LGE	0.8	1	60,438	35.5	216
Brisbane	HGSHP1 system	Min NPC	0.34	0.34	41,125	55.4	84
		EW	0.56	0.56	42,070	49.1	126
		Min LGE	0.9	0.9	45,798	47.6	181
	HGSHP2 system	Min NPC	0.56	0.56	45,403	48.7	126
		EW	0.68	0.7	45,635	47.8	147
		Min LGE	0.84	0.92	46,409	47.6	174
Cairns	HGSHP1 system	Min NPC	1	0.38	66,121	99.6	152
		EW	1	0.6	67,052	89.6	211
		Min LGE	1	0.92	70,337	86.9	266
	HGSHP2 system	N/A					
Hobart	HGSHP1 system	Min NPC	0.24	0.36	61,073	20	119
		EW	0.46	0.7	62,166	17.7	197
		Min LGE	0.78	1	65,650	17	267
	HGSHP2 system	Min NPC	0.64	1	61,973	18.3	242
		EW	0.72	1	62,866	17.3	257
		Min LGE	0.84	1	65,011	16.9	276
Melbourne	HGSHP1 system	Min NPC	0.44	0.66	67,793	109.8	183
		EW	0.62	0.92	68,827	102	230
		Min LGE	0.92	1	72,166	100	282
	HGSHP2 system	Min NPC	0.52	1	66,080	98.2	206
		EW	0.18	0.66	68,779	92	84
		Min LGE	0	0.9	82,604	86	118
Perth	HGSHP1 system	Min NPC	0.34	0.36	49,583	50	106
		EW	0.52	0.54	50,603	45.7	147
		Min LGE	0.86	0.88	54,791	44.5	207
	HGSHP2 system	Min NPC	0.44	0.6	54,104	45.3	129
		EW	0.58	0.8	54,379	44.4	159
		Min LGE	0.72	1	55,013	44.2	184
Sydney	HGSHP1 system	Min NPC	0.32	0.32	39,917	51.8	76
		EW	0.54	0.54	40,780	45.7	117
		Min LGE	0.88	0.9	43,944	43.9	167
	HGSHP2 system	Min NPC	0.6	0.6	43,963	44.3	127
		EW	0.68	0.7	44,020	44	140
		Min LGE	0.82	0.86	44,514	43.8	160

Effect of changes in drilling costs

Location	Drilling cost (\$/m)	Category	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Adelaide	50	HGSH1 system	Min NPC	0.56	0.62	52,819	36.6	175
			EW	0.68	0.74	53,178	35.9	197
			Min LGE	0.84	0.92	54,123	35.6	222
		HGSH2 system	Min NPC	0.9	1	53,856	35.6	230
			EW	0.84	1	53,908	35.5	222
			Min LGE	0.8	1	53,953	35.5	216
	80	HGSH1 system	Min NPC	0.44	0.48	57,644	38.6	148
			EW	0.6	0.66	58,365	36.3	183
			Min LGE	0.84	0.92	60,782	35.6	222
		HGSH2 system	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
	100	HGSH1 system	Min NPC	0.36	0.4	60,354	40.6	126
			EW	0.56	0.62	61,567	36.6	175
			Min LGE	0.84	0.92	65,221	35.6	222
		HGSH2 system	Min NPC	0.52	1	63,525	36.8	166
			EW	0.64	1	63,873	35.8	190
			Min LGE	0.8	1	64,762	35.5	216
150	HGSH1 system	Min NPC	0.14	0.2	65,195	50.5	55	
		EW	0.42	0.46	67,623	39	143	
		Min LGE	0.84	0.92	76,319	35.6	222	
	HGSH2 system	Min NPC	0.3	0.66	70,239	42	107	
		EW	0.52	1	71,825	36.8	166	
		Min LGE	0.8	1	75,571	35.5	216	
Brisbane	50	HGSH1 system	Min NPC	0.48	0.48	38,169	50.7	112
			EW	0.64	0.64	38,667	48.3	140
			Min LGE	0.9	0.9	40,371	47.6	181
		HGSH2 system	Min NPC	1	1	41,064	47.7	195
			EW	0.84	0.9	41,096	47.6	172
			Min LGE	0.84	0.92	41,190	47.6	174
	80	HGSH1 system	Min NPC	0.34	0.34	41,125	55.4	84
			EW	0.56	0.56	42,070	49.1	126
			Min LGE	0.9	0.9	45,798	47.6	181
		HGSH2 system	Min NPC	0.56	0.56	45,403	48.7	126
			EW	0.68	0.7	45,635	47.8	147
			Min LGE	0.84	0.92	46,409	47.6	174
	100	HGSH1 system	Min NPC	0.26	0.26	42,638	59.6	67
			EW	0.52	0.52	44,156	49.8	119
			Min LGE	0.9	0.9	49,415	47.6	181
		HGSH2 system	Min NPC	0.5	0.5	47,829	49.6	116
			EW	0.66	0.68	48,472	47.9	144
			Min LGE	0.84	0.92	49,889	47.6	174
	150	HGSH1 system	Min NPC	0.06	0.06	44,725	76.3	17
			EW	0.4	0.4	47,966	53	97
			Min LGE	0.9	0.9	58,460	47.6	181
		HGSH2 system	Min NPC	0.3	0.3	52,582	55	76
			EW	0.54	0.54	54,002	49	123
			Min LGE	0.84	0.92	58,588	47.6	174

Location	Drilling cost (\$/m)	Category	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)	
Cairns	50	HGSH1 system	Min NPC	1	0.56	60,685	90.7	202	
			EW	1	0.7	61,058	87.9	232	
			Min LGE	1	0.92	62,357	86.9	266	
			HGSH2 system	N/A					
	80	HGSH1 system	Min NPC	1	0.38	66,121	99.6	152	
			EW	1	0.6	67,052	89.6	211	
			Min LGE	1	0.92	70,337	86.9	266	
			HGSH2 system	N/A					
	100	HGSH1 system	Min NPC	0.64	0.24	68,711	111.4	103	
			EW	1	0.52	70,346	92.1	192	
			Min LGE	1	0.92	75,656	86.9	266	
			HGSH2 system	N/A					
150	HGSH1 system	Min NPC	0	0	70,158	142.6	0		
		EW	1	0.38	76,778	99.6	152		
		Min LGE	1	0.92	88,956	86.9	266		
		HGSH2 system	N/A						
Hobart	50	HGSH1 system	Min NPC	0.46	0.7	56,252	17.7	197	
			EW	0.6	0.92	56,599	17.2	233	
			Min LGE	0.78	1	57,647	17	267	
	HGSH2 system	Min NPC	0.66	1	54,666	18	246		
		EW	0.74	1	55,379	17.1	260		
		Min LGE	0.84	1	56,732	16.9	276		
	80	HGSH1 system	Min NPC	0.24	0.36	61,073	20	119	
			EW	0.46	0.7	62,166	17.7	197	
			Min LGE	0.78	1	65,650	17	267	
	HGSH2 system	Min NPC	0.64	1	61,973	18.3	242		
		EW	0.72	1	62,866	17.3	257		
		Min LGE	0.84	1	65,011	16.9	276		
	100	HGSH1 system	Min NPC	0.04	0.06	62,571	23.9	22	
			EW	0.34	0.52	64,489	18.7	158	
			Min LGE	0.78	1	70,986	17	267	
	HGSH2 system	Min NPC	0.64	1	66,804	18.3	242		
		EW	0.72	1	68,003	17.3	257		
		Min LGE	0.84	1	70,530	16.9	276		
150	HGSH1 system	Min NPC	0	0	62,623	24.9	0		
		EW	0.32	0.48	71,775	18.9	150		
		Min LGE	0.78	1	84,326	17	267		
HGSH2 system	Min NPC	0.52	1	78,312	21.7	214			
	EW	0.66	1	79,231	18	246			
	Min LGE	0.84	1	84,329	16.9	276			

Location	Drilling cost (\$/m)	Category	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Melbourne	50	HGSHP1 system	Min NPC	0.56	0.84	61,806	103.7	216
			EW	0.7	1	62,278	100.8	247
			Min LGE	0.92	1	63,720	100	282
		HGSHP2 system	Min NPC	0.66	1	59,173	99.2	239
			EW	0.2	0.76	65,629	92.4	94
			Min LGE	0	0.9	79,049	86	118
	80	HGSHP1 system	Min NPC	0.44	0.66	67,793	109.8	183
			EW	0.62	0.92	68,827	102	230
			Min LGE	0.92	1	72,166	100	282
		HGSHP2 system	Min NPC	0.52	1	66,080	98.2	206
			EW	0.18	0.66	68,779	92	84
			Min LGE	0	0.9	82,604	86	118
	100	HGSHP1 system	Min NPC	0.32	0.48	71,142	120.3	144
			EW	0.56	0.84	72,618	103.7	216
			Min LGE	0.92	1	77,797	100	282
		HGSHP2 system	Min NPC	0.36	1	69,819	95.9	157
			EW	0.16	0.58	70,734	91.7	75
			Min LGE	0	0.9	84,973	86	118
150	HGSHP1 system	Min NPC	0	0	75,969	176.1	0	
		EW	0.36	0.54	80,417	121.7	155	
		Min LGE	0.92	1	93,496	106.9	277	
	HGSHP2 system	Min NPC	0.12	0.42	74,382	91.4	57	
		EW	0	0.5	84,561	86.8	74	
		Min LGE	0	0.9	90,898	86	118	
Perth	50	HGSHP1 system	Min NPC	0.44	0.46	46,009	47	130
			EW	0.6	0.62	46,622	45	163
			Min LGE	0.86	0.88	48,590	44.5	207
		HGSHP2 system	Min NPC	1	1	49,350	44.5	227
			EW	0.9	1	49,415	44.4	213
			Min LGE	0.72	1	49,480	44.2	184
	80	HGSHP1 system	Min NPC	0.34	0.36	49,583	50	106
			EW	0.52	0.54	50,603	45.7	147
			Min LGE	0.86	0.88	54,791	44.5	207
		HGSHP2 system	Min NPC	0.44	0.6	54,104	45.3	129
			EW	0.58	0.8	54,379	44.4	159
			Min LGE	0.72	1	55,013	44.2	184
	100	HGSHP1 system	Min NPC	0.24	0.28	51,448	54.4	78
			EW	0.48	0.5	52,998	46.2	139
			Min LGE	0.86	0.88	58,925	44.5	207
		HGSHP2 system	Min NPC	0.4	0.54	56,581	45.7	120
			EW	0.52	0.72	57,136	44.7	147
			Min LGE	0.72	1	58,702	44.2	184
150	HGSHP1 system	Min NPC	0.14	0.18	54,335	61.3	47	
		EW	0.42	0.44	58,600	47.4	126	
		Min LGE	0.86	0.88	69,261	44.5	207	
	HGSHP2 system	Min NPC	0.26	0.34	61,465	49.2	83	
		EW	0.44	0.6	63,158	45.3	129	
		Min LGE	0.72	1	67,925	44.2	184	

Location	Drilling cost (\$/m)	Category	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Sydney	50	HGSHP1 system	Min NPC	0.46	0.46	37,170	47.3	103
			EW	0.64	0.66	37,618	44.5	134
			Min LGE	0.88	0.9	38,944	43.9	167
		HGSHP2 system	Min NPC	0.88	0.9	39,651	43.8	167
			EW	0.84	0.86	39,653	43.8	162
			Min LGE	0.82	0.86	39,708	43.8	160
	80	HGSHP1 system	Min NPC	0.32	0.32	39,917	51.8	76
			EW	0.54	0.54	40,780	45.7	117
			Min LGE	0.88	0.9	43,944	43.9	167
		HGSHP2 system	Min NPC	0.6	0.6	43,963	44.3	127
			EW	0.68	0.7	44,020	44	140
			Min LGE	0.82	0.86	44,514	43.8	160
	100	HGSHP1 system	Min NPC	0.24	0.24	41,288	55.8	60
			EW	0.5	0.5	42,699	46.4	110
			Min LGE	0.88	0.9	47,278	43.9	167
	HGSHP2 system	Min NPC	0.52	0.52	46,393	44.9	114	
		EW	0.66	0.68	46,740	44	137	
		Min LGE	0.82	0.86	47,718	43.8	160	
150	HGSHP1 system	Min NPC	0.06	0.06	43,283	70.1	16	
		EW	0.38	0.38	46,162	49.6	88	
		Min LGE	0.88	0.9	55,611	43.9	167	
	HGSHP2 system	Min NPC	0.36	0.36	51,409	47.1	84	
		EW	0.54	0.54	52,260	44.7	117	
		Min LGE	0.82	0.86	55,728	43.8	160	

Effect of changes in energy prices

Location	Category	Energy prices	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO ₂ e)	GHE Length (m)
Adelaide	HGSHP1 system	1e	Min NPC	0.44	0.48	57,644	38.6	148
			EW	0.6	0.66	58,365	36.3	183
			Min LGE	0.84	0.92	60,782	35.6	222
		2e	Min NPC	0.58	0.64	87,273	36.4	179
			EW	0.7	0.76	87,732	35.8	201
			Min LGE	0.84	0.92	89,001	35.6	222
	HGSHP2 system	1e1g	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
		1e2g	Min NPC	0.24	0.52	84,074	44.6	88
			EW	0.42	0.96	85,790	38.5	142
			Min LGE	0.8	1	88,555	35.5	216
		2e1g	Min NPC	0.78	1	60,572	35.5	213
			EW	0.8	1	60,588	35.5	216
			Min LGE	0.8	1	60,588	35.5	216
		2e2g	Min NPC	0.74	1	88,623	35.5	207
			EW	0.76	1	88,638	35.5	210
			Min LGE	0.8	1	88,704	35.5	216
Brisbane	HGSHP1 system	1e	Min NPC	0.34	0.34	41,125	55.4	84
			EW	0.56	0.56	42,070	49.1	126
			Min LGE	0.9	0.9	45,798	47.6	181
		2e	Min NPC	0.54	0.54	59,521	49.4	123
			EW	0.68	0.68	60,379	48.1	147
			Min LGE	0.9	0.9	62,646	47.6	181
	HGSHP2 system	1e1g	Min NPC	0.56	0.56	45,403	48.7	126
			EW	0.68	0.7	45,635	47.8	147
			Min LGE	0.84	0.92	46,409	47.6	174
		1e2g	Min NPC	0.58	0.58	62,432	48.5	130
			EW	0.68	0.7	62,510	47.8	147
			Min LGE	0.84	0.92	63,237	47.6	174
		2e1g	Min NPC	0.68	0.7	45,860	47.8	147
			EW	0.76	0.8	46,024	47.6	160
			Min LGE	0.84	0.92	46,446	47.6	174
		2e2g	Min NPC	0.68	0.7	62,735	47.8	147
			EW	0.76	0.8	62,858	47.6	160
			Min LGE	0.84	0.92	63,273	47.6	174

Location	Category	Energy prices	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO ₂ e)	GHE Length (m)
Cairns	HGSHP1 system	1e	Min NPC	1	0.38	66,121	99.6	152
			EW	1	0.6	67,052	89.6	211
			Min LGE	1	0.92	70,337	86.9	266
	2e	Min NPC	1	0.62	99,178	89.1	216	
		EW	1	0.74	99,739	87.5	239	
		Min LGE	1	0.92	101,380	86.9	266	
HGSHP2 system	N/A							
Hobart	HGSHP1 system	1e	Min NPC	0.24	0.36	61,073	20	119
			EW	0.46	0.7	62,166	17.7	197
			Min LGE	0.78	1	65,650	17	267
		2e	Min NPC	0.52	0.8	91,170	17.4	214
			EW	0.64	0.98	91,559	17.1	242
			Min LGE	0.78	1	92,761	17	267
	HGSHP2 system	1e1g	Min NPC	0.64	1	61,973	18.3	242
			EW	0.72	1	62,866	17.3	257
			Min LGE	0.84	1	65,011	16.9	276
		1e2g	Min NPC	0.58	1	88,278	19.7	228
			EW	0.68	1	88,888	17.7	250
			Min LGE	0.84	1	92,013	16.9	276
	2e1g	Min NPC	0.7	1	63,553	17.5	253	
		EW	0.76	1	63,940	17	264	
		Min LGE	0.84	1	65,121	16.9	276	
	2e2g	Min NPC	0.66	1	90,146	18	246	
		EW	0.74	1	90,591	17.1	260	
		Min LGE	0.84	1	92,124	16.9	276	
Melbourne	HGSHP1 system	1e	Min NPC	0.44	0.66	67,793	109.8	183
			EW	0.62	0.92	68,827	102	230
			Min LGE	0.92	1	72,166	100	282
		2e	Min NPC	0.6	0.9	102,479	102.5	226
			EW	0.72	1	103,046	100.6	250
			Min LGE	0.92	1	105,084	100	282
	HGSHP2 system	1e1g	Min NPC	0.52	1	66,080	98.2	206
			EW	0.18	0.66	68,779	92	84
			Min LGE	0	0.9	82,604	86	118
		1e2g	Min NPC	0	0.08	81,639	91.6	14
			EW	0	0.44	82,705	87.2	66
			Min LGE	0	0.9	85,922	86	118
	2e1g	Min NPC	0.66	1	67,392	99.2	239	
		EW	0.22	0.84	90,903	92.8	102	
		Min LGE	0	0.9	133,008	86	118	
	2e2g	Min NPC	0.66	1	99,686	99.2	239	
		EW	0.2	0.76	111,653	92.4	94	
		Min LGE	0	0.9	136,326	86	118	

Location	Category	Energy prices	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO ₂ e)	GHE Length (m)
Perth	HGSHP1 system	1e	Min NPC	0.34	0.36	49,583	50	106
			EW	0.52	0.54	50,603	45.7	147
			Min LGE	0.86	0.88	54,791	44.5	207
		2e	Min NPC	0.48	0.5	73,029	46.2	139
			EW	0.62	0.64	73,811	44.9	167
			Min LGE	0.86	0.88	76,532	44.5	207
	HGSHP2 system	1e1g	Min NPC	0.44	0.6	54,104	45.3	129
			EW	0.58	0.8	54,379	44.4	159
			Min LGE	0.72	1	55,013	44.2	184
		1e2g	Min NPC	0.3	0.4	74,318	47.8	95
			EW	0.44	0.6	74,788	45.3	129
			Min LGE	0.72	1	76,663	44.2	184
		2e1g	Min NPC	0.62	0.86	54,994	44.3	167
			EW	0.68	0.94	55,051	44.3	177
			Min LGE	0.72	1	55,154	44.2	184
		2e2g	Min NPC	0.58	0.8	76,473	44.4	159
			EW	0.62	0.86	76,505	44.3	167
			Min LGE	0.72	1	76,804	44.2	184
Sydney	HGSHP1 system	1e	Min NPC	0.32	0.32	39,917	51.8	76
			EW	0.54	0.54	40,780	45.7	117
			Min LGE	0.88	0.9	43,944	43.9	167
		2e	Min NPC	0.52	0.52	57,514	46.1	114
			EW	0.66	0.68	58,009	44.4	137
			Min LGE	0.88	0.9	59,900	43.9	167
	HGSHP2 system	1e1g	Min NPC	0.6	0.6	43,963	44.3	127
			EW	0.68	0.7	44,020	44	140
			Min LGE	0.82	0.86	44,514	43.8	160
		1e2g	Min NPC	0.56	0.56	59,694	44.6	121
			EW	0.68	0.7	59,861	44	140
			Min LGE	0.82	0.86	60,448	43.8	160
		2e1g	Min NPC	0.74	0.76	44,404	43.9	148
			EW	0.78	0.8	44,421	43.9	154
			Min LGE	0.82	0.86	44,573	43.8	160
		2e2g	Min NPC	0.72	0.74	60,295	43.9	146
			EW	0.78	0.8	60,340	43.9	154
			Min LGE	0.82	0.86	60,506	43.8	160

Effect of changes in ground thermal conductivity

Location	Category	Thermal conductivity (W/m.K)	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Adelaide	HGSHP1 system	2.5	Min NPC	0.44	0.48	57,644	38.6	148
			EW	0.6	0.66	58,365	36.3	183
			Min LGE	0.84	0.92	60,782	35.6	222
		2.0	Min NPC	0.38	0.42	59,364	40.2	153
			EW	0.56	0.62	60,164	36.8	201
			Min LGE	0.84	0.92	63,248	35.9	253
		1.5	Min NPC	0.32	0.36	61,918	42.3	162
			EW	0.54	0.6	63,317	37.4	238
			Min LGE	0.82	0.9	66,918	36.3	299
	1.0	Min NPC	0.1	0.2	65,283	53	72	
		EW	0.38	0.42	67,041	41	248	
		Min LGE	0.8	0.88	73,958	37	386	
	0.7	Min NPC	0.06	0.12	66,232	56.3	52	
		EW	0.36	0.4	70,936	41.9	290	
		Min LGE	0.78	0.86	79,787	37.6	459	
	HGSHP2 system	2.5	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
		2.0	Min NPC	0.56	1	62,175	36.6	201
			EW	0.66	1	62,353	36	222
			Min LGE	0.8	1	62,866	35.7	247
		1.5	Min NPC	0.48	1	65,397	37.9	219
			EW	0.6	1	65,687	36.6	253
			Min LGE	0.78	1	66,628	36.1	291
1.0		Min NPC	0.28	0.74	70,226	43.4	189	
		EW	0.48	1	71,210	38.4	291	
		Min LGE	0.76	1	73,708	36.8	378	
0.7		Min NPC	0.22	0.56	73,093	46.2	185	
		EW	0.42	1	75,328	39.9	321	
		Min LGE	0.76	1	79,810	37.4	454	
Brisbane	HGSHP1 system	2.5	Min NPC	0.34	0.34	41,125	55.4	84
			EW	0.56	0.56	42,070	49.1	126
			Min LGE	0.9	0.9	45,798	47.6	181
		2.0	Min NPC	0.3	0.3	42,074	57.5	87
			EW	0.54	0.54	43,307	49.6	140
			Min LGE	0.88	0.88	47,137	47.8	198
		1.5	Min NPC	0.22	0.22	43,330	62.4	80
			EW	0.48	0.48	44,895	51	154
			Min LGE	0.88	0.88	49,578	48	228
	1.0	Min NPC	0.06	0.06	44,723	76.4	31	
		EW	0.38	0.38	47,282	54.4	169	
		Min LGE	0.9	0.88	54,885	48.5	292	
	0.7	Min NPC	0	0	44,920	83.5	0	
		EW	0.34	0.3	48,756	57.4	167	
		Min LGE	0.88	0.86	59,013	48.9	344	

Location	Category	Thermal conductivity (W/m.K)	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Brisbane	HGSHP2 system	2.5	Min NPC	0.56	0.56	45,403	48.7	126
			EW	0.68	0.7	45,635	47.8	147
			Min LGE	0.84	0.92	46,409	47.6	174
		2.0	Min NPC	0.54	0.54	46,814	49.1	140
			EW	0.68	0.68	47,006	48.1	164
			Min LGE	0.84	0.88	47,812	47.7	191
		1.5	Min NPC	0.46	0.44	48,907	51	144
			EW	0.6	0.6	49,233	48.7	181
			Min LGE	0.86	0.88	50,475	48	227
	1.0	Min NPC	0.36	0.32	52,060	54.6	146	
		EW	0.54	0.52	53,116	50	215	
		Min LGE	0.86	0.86	55,465	48.5	289	
	0.7	Min NPC	0.3	0.26	54,149	57	148	
		EW	0.5	0.48	56,145	50.9	244	
		Min LGE	0.84	0.84	59,699	48.9	340	
Cairns	HGSHP1 system	2.5	Min NPC	1	0.38	66,121	99.6	152
			EW	1	0.6	67,052	89.6	211
			Min LGE	1	0.92	70,337	86.9	266
		2.0	Min NPC	0.8	0.3	68,020	105.9	147
			EW	1	0.56	69,424	91	236
			Min LGE	1	0.92	73,583	87.2	307
		1.5	Min NPC	0.26	0.1	69,905	128	66
			EW	1	0.44	72,226	96.5	246
			Min LGE	1	0.92	78,801	87.7	372
	1.0	Min NPC	0	0	70,158	142.6	0	
		EW	0.96	0.36	77,583	102.1	289	
		Min LGE	1	0.9	88,443	88.7	492	
	0.7	Min NPC	0	0	70,158	142.6	0	
		EW	0.96	0.36	82,949	102.6	356	
		Min LGE	1	0.9	96,898	89.5	598	
	HGSHP2 system	N/A						
Hobart	HGSHP1 system	2.5	Min NPC	0.24	0.36	61,073	20	119
			EW	0.46	0.7	62,166	17.7	197
			Min LGE	0.78	1	65,650	17	267
		2.0	Min NPC	0.12	0.18	62,351	22.2	74
			EW	0.38	0.58	63,878	18.5	201
			Min LGE	0.76	1	68,668	17.3	304
		1.5	Min NPC	0	0	62,623	24.9	0
			EW	0.3	0.46	66,295	19.6	207
			Min LGE	0.74	1	73,608	17.8	366
	1.0	Min NPC	0	0	62,623	24.9	0	
		EW	0.3	0.46	72,391	20.2	283	
		Min LGE	0.7	1	82,768	18.8	479	
	0.7	Min NPC	0	0	62,623	24.9	0	
		EW	0.28	0.42	76,750	20.9	330	
		Min LGE	0.68	1	90,672	19.6	577	

Location	Category	Thermal conductivity (W/m.K)	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Hobart	HGSHP2 system	2.5	Min NPC	0.64	1	61,973	18.3	242
			EW	0.72	1	62,866	17.3	257
			Min LGE	0.84	1	65,011	16.9	276
		2.0	Min NPC	0.64	1	65,049	18.6	280
			EW	0.72	1	66,068	17.6	297
			Min LGE	0.84	1	68,339	17.2	318
		1.5	Min NPC	0.64	1	70,008	19.1	342
			EW	0.72	1	71,223	18.1	361
			Min LGE	0.84	1	73,686	17.7	384
	1.0	Min NPC	0.56	1	79,315	21.9	431	
		EW	0.66	1	79,740	19.7	467	
		Min LGE	0.84	1	83,852	18.7	511	
	0.7	Min NPC	0.44	1	86,629	27.9	459	
		EW	0.64	1	87,616	20.8	562	
		Min LGE	0.82	1	92,034	19.6	616	
Melbourne	HGSHP1 system	2.5	Min NPC	0.44	0.66	67,793	109.8	183
			EW	0.62	0.92	68,827	102	230
			Min LGE	0.92	1	72,166	100	282
		2.0	Min NPC	0.36	0.54	70,101	116.5	184
			EW	0.56	0.84	71,057	104	251
			Min LGE	0.9	1	75,215	100.4	320
		1.5	Min NPC	0.24	0.36	73,183	130.6	162
			EW	0.5	0.74	74,720	106.9	286
			Min LGE	0.9	1	80,456	100.9	385
		1.0	Min NPC	0.02	0.06	75,932	170.8	19
			EW	0.36	0.54	79,995	117.5	308
			Min LGE	0.88	1	90,076	101.8	505
		0.7	Min NPC	0	0	75,969	176.1	0
			EW	0.34	0.52	85,018	119.8	362
			Min LGE	0.86	1	98,152	102.6	606
	HGSHP2 system	2.5	Min NPC	0.52	1	66,080	98.2	206
			EW	0.18	0.66	68,779	92	84
			Min LGE	0	0.9	82,604	86	118
		2.0	Min NPC	0.44	1	68,640	97.5	213
			EW	0.16	0.62	70,230	91.6	88
			Min LGE	0	0.88	83,505	86.1	130
		1.5	Min NPC	0.2	0.88	71,606	92.5	134
			EW	0.12	0.5	72,532	91	86
			Min LGE	0	0.86	84,972	86.3	148
		1.0	Min NPC	0.12	0.5	74,381	91.2	109
			EW	0	0.5	83,355	87.2	124
			Min LGE	0	0.84	87,756	86.6	183
0.7	Min NPC	0.06	0.24	75,533	91.5	66		
	EW	0	0.46	84,460	87.6	136		
	Min LGE	0	0.8	89,672	86.8	207		

Location	Category	Thermal conductivity (W/m.K)	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Perth	HGSHP1 system	2.5	Min NPC	0.34	0.36	49,583	50	106
			EW	0.52	0.54	50,603	45.7	147
			Min LGE	0.86	0.88	54,791	44.5	207
		2.0	Min NPC	0.28	0.32	50,701	52.3	102
			EW	0.5	0.52	51,937	46.1	162
			Min LGE	0.84	0.86	56,552	44.7	229
		1.5	Min NPC	0.22	0.26	52,148	55.8	99
			EW	0.46	0.48	53,826	47	182
			Min LGE	0.82	0.84	59,420	45	265
	1.0	Min NPC	0.14	0.18	53,983	61.6	84	
		EW	0.42	0.44	57,447	48.2	221	
		Min LGE	0.78	0.84	65,144	45.5	328	
	0.7	Min NPC	0.08	0.1	55,122	67.6	60	
		EW	0.3	0.4	58,545	51.4	199	
		Min LGE	0.76	0.84	69,802	46	382	
	HGSHP2 system	2.5	Min NPC	0.44	0.6	54,104	45.3	129
			EW	0.58	0.8	54,379	44.4	159
			Min LGE	0.72	1	55,013	44.2	184
		2.0	Min NPC	0.4	0.54	55,488	45.9	136
			EW	0.52	0.72	55,744	44.8	166
			Min LGE	0.7	0.98	56,756	44.4	204
		1.5	Min NPC	0.38	0.52	57,490	46.3	156
			EW	0.52	0.74	58,203	45	197
			Min LGE	0.7	1	59,671	44.7	240
1.0		Min NPC	0.3	0.4	60,774	48.4	166	
		EW	0.44	0.62	61,837	46	226	
		Min LGE	0.66	0.98	64,629	45.2	298	
0.7		Min NPC	0.2	0.26	62,947	52.2	140	
		EW	0.36	0.5	64,014	47.2	231	
		Min LGE	0.66	1	69,033	45.6	353	
Sydney	HGSHP1 system	2.5	Min NPC	0.32	0.32	39,917	51.8	76
			EW	0.54	0.54	40,780	45.7	117
			Min LGE	0.88	0.9	43,944	43.9	167
		2.0	Min NPC	0.28	0.28	40,740	53.7	78
			EW	0.52	0.52	41,843	46.2	129
			Min LGE	0.88	0.9	45,593	44	187
		1.5	Min NPC	0.22	0.22	41,876	57.2	76
			EW	0.5	0.5	43,556	46.7	148
			Min LGE	0.86	0.88	47,956	44.3	217
	1.0	Min NPC	0.08	0.08	43,236	68.2	39	
		EW	0.38	0.36	45,362	50.4	154	
		Min LGE	0.84	0.86	52,437	44.7	273	
	0.7	Min NPC	0	0	43,480	76.9	0	
		EW	0.32	0.3	46,671	52.9	159	
		Min LGE	0.82	0.84	56,042	45.1	318	

Location	Category	Thermal conductivity (W/m.K)	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Sydney	HGSHP2 system	2.5	Min NPC	0.6	0.6	43,963	44.3	127
			EW	0.68	0.7	44,020	44	140
			Min LGE	0.82	0.86	44,514	43.8	160
		2.0	Min NPC	0.56	0.56	45,281	44.7	137
			EW	0.68	0.7	45,470	44.1	158
			Min LGE	0.82	0.86	46,120	44	180
		1.5	Min NPC	0.52	0.52	47,246	45.2	153
			EW	0.66	0.68	47,710	44.4	183
			Min LGE	0.8	0.84	48,556	44.2	209
	1.0	Min NPC	0.4	0.38	50,608	47.2	161	
		EW	0.56	0.56	51,074	45.2	209	
		Min LGE	0.78	0.82	53,082	44.7	264	
	0.7	Min NPC	0.32	0.3	52,857	49	159	
		EW	0.52	0.52	53,986	45.8	237	
		Min LGE	0.76	0.78	56,462	45.1	304	

Effect of changes in CoPs of RCAC

Location	Category	CoPs of RCAC	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Adelaide	HGSHP1 system	+ 0.5	Min NPC	0.26	0.28	55,893	41	97
			EW	0.5	0.54	57,102	36.7	162
			Min LGE	0.82	0.9	60,549	35.6	219
		Base case	Min NPC	0.44	0.48	57,644	38.6	148
			EW	0.6	0.66	58,365	36.3	183
			Min LGE	0.84	0.92	60,782	35.6	222
		- 0.5	Min NPC	0.56	0.62	58,650	37.3	175
			EW	0.7	0.76	59,434	36	201
			Min LGE	0.88	0.96	61,223	35.7	228
	HGSHP2 system	+ 0.5	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
		Base case	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
		- 0.5	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
Brisbane	HGSHP1 system	+ 0.5	Min NPC	0.16	0.16	39,414	59.6	43
			EW	0.46	0.46	40,908	49.8	108
			Min LGE	0.86	0.86	45,336	47.6	175
		Base case	Min NPC	0.34	0.34	41,125	55.4	84
			EW	0.56	0.56	42,070	49.1	126
			Min LGE	0.9	0.9	45,798	47.6	181
		- 0.5	Min NPC	0.48	0.48	42,195	52.5	112
			EW	0.64	0.64	43,054	48.8	140
			Min LGE	0.92	0.92	46,025	47.6	184
	HGSHP2 system	+ 0.5	Min NPC	0.54	0.54	45,220	48.4	123
			EW	0.66	0.68	45,537	47.8	144
			Min LGE	0.82	0.88	46,188	47.5	169
		Base case	Min NPC	0.56	0.56	45,403	48.7	126
			EW	0.68	0.7	45,635	47.8	147
			Min LGE	0.84	0.92	46,409	47.6	174
		- 0.5	Min NPC	0.6	0.6	45,627	48.8	133
			EW	0.7	0.72	45,760	47.9	150
			Min LGE	0.84	0.92	46,410	47.6	174
Cairns	HGSHP1 system	+ 0.5	Min NPC	0	0	61,467	119	0
			EW	1	0.38	64,108	94.1	152
			Min LGE	1	0.92	70,334	86.9	266
		Base case	Min NPC	1	0.38	66,121	99.6	152
			EW	1	0.6	67,052	89.6	211
			Min LGE	1	0.92	70,337	86.9	266
		- 0.5	Min NPC	1	0.56	67,692	93.3	202
			EW	1	0.7	68,269	88.6	232
			Min LGE	1	0.94	70,538	86.9	269
	HGSHP2 system	N/A						

Location	Category	CoPs of RCAC	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Hobart	HGSHP1 system	+ 0.5	Min NPC	0	0	55,052	21	0
			EW	0.3	0.46	58,901	18	143
			Min LGE	0.72	1	64,886	17	257
		Base case	Min NPC	0.24	0.36	61,073	20	119
			EW	0.46	0.7	62,166	17.7	197
			Min LGE	0.78	1	65,650	17	267
		- 0.5	Min NPC	0.46	0.7	63,499	18.4	197
			EW	0.62	0.94	64,176	17.3	237
			Min LGE	0.82	1	66,135	17	273
	HGSHP2 system	+ 0.5	Min NPC	0.64	1	61,973	18.3	242
			EW	0.72	1	62,866	17.3	257
			Min LGE	0.84	1	65,011	16.9	276
		Base case	Min NPC	0.64	1	61,973	18.3	242
			EW	0.72	1	62,866	17.3	257
			Min LGE	0.84	1	65,011	16.9	276
		- 0.5	Min NPC	0.64	1	61,973	18.3	242
			EW	0.72	1	62,866	17.3	257
			Min LGE	0.84	1	65,011	16.9	276
Melbourne	HGSHP1 system	+ 0.5	Min NPC	0.2	0.3	65,159	122.2	96
			EW	0.48	0.72	66,876	104.4	195
			Min LGE	0.88	1	71,716	100	276
		Base case	Min NPC	0.44	0.66	67,793	109.8	183
			EW	0.62	0.92	68,827	102	230
			Min LGE	0.92	1	72,166	100	282
		- 0.5	Min NPC	0.56	0.84	69,055	106	216
			EW	0.7	1	69,849	101.3	247
			Min LGE	0.94	1	72,387	100	284
	HGSHP2 system	+ 0.5	Min NPC	0.52	1	66,080	98.2	206
			EW	0.16	0.58	69,156	91.5	75
			Min LGE	0	0.86	82,282	86	114
		Base case	Min NPC	0.52	1	66,080	98.2	206
			EW	0.18	0.66	68,779	92	84
			Min LGE	0	0.9	82,604	86	118
		- 0.5	Min NPC	0.52	1	66,080	98.2	206
			EW	0.2	0.76	68,466	92.4	94
			Min LGE	0	0.92	82,763	86	120

Location	Category	CoPs of RCAC	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Perth	HGSHP1 system	+ 0.5	Min NPC	0.16	0.2	47,709	53.9	54
			EW	0.42	0.44	49,169	46.2	126
			Min LGE	0.8	0.82	54,027	44.5	198
		Base case	Min NPC	0.34	0.36	49,583	50	106
			EW	0.52	0.54	50,603	45.7	147
			Min LGE	0.86	0.88	54,791	44.5	207
		- 0.5	Min NPC	0.44	0.46	50,716	48.5	130
			EW	0.6	0.62	51,724	45.4	163
			Min LGE	0.9	0.92	55,286	44.5	213
	HGSHP2 system	+ 0.5	Min NPC	0.44	0.6	54,037	45.1	129
			EW	0.58	0.8	54,366	44.4	159
			Min LGE	0.72	1	55,013	44.2	184
		Base case	Min NPC	0.44	0.6	54,104	45.3	129
			EW	0.58	0.8	54,379	44.4	159
			Min LGE	0.72	1	55,013	44.2	184
- 0.5		Min NPC	0.48	0.66	54,178	45	138	
		EW	0.58	0.8	54,397	44.5	159	
		Min LGE	0.72	1	55,013	44.2	184	
Sydney	HGSHP1 system	+ 0.5	Min NPC	0.16	0.16	38,257	54.7	41
			EW	0.44	0.44	39,578	46.3	99
			Min LGE	0.86	0.88	43,744	43.8	164
		Base case	Min NPC	0.32	0.32	39,917	51.8	76
			EW	0.54	0.54	40,780	45.7	117
			Min LGE	0.88	0.9	43,944	43.9	167
		- 0.5	Min NPC	0.46	0.46	41,015	49.3	103
			EW	0.64	0.66	41,808	44.9	134
			Min LGE	0.9	0.92	44,141	43.9	169
	HGSHP2 system	+ 0.5	Min NPC	0.58	0.58	43,897	44.2	124
			EW	0.68	0.7	43,996	43.9	140
			Min LGE	0.82	0.86	44,511	43.8	160
		Base case	Min NPC	0.6	0.6	43,963	44.3	127
			EW	0.68	0.7	44,020	44	140
			Min LGE	0.82	0.86	44,514	43.8	160
- 0.5		Min NPC	0.66	0.68	44,044	44.1	137	
		EW	0.76	0.78	44,243	43.9	151	
		Min LGE	0.86	0.9	44,646	43.8	165	

Effect of changes in CoPs of GSHP

Location	Category	CoPs of GSHP	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Adelaide	HGSHP1 system	+ 0.5	Min NPC	0.46	0.5	55,524	35.3	157
			EW	0.62	0.68	56,237	33	192
			Min LGE	0.86	0.94	58,679	32.4	230
		Base case	Min NPC	0.44	0.48	57,644	38.6	148
			EW	0.6	0.66	58,365	36.3	183
			Min LGE	0.84	0.92	60,782	35.6	222
		- 0.5	Min NPC	0.38	0.42	60,179	43.4	127
			EW	0.56	0.62	60,883	40.5	169
			Min LGE	0.84	0.92	63,664	39.6	215
	HGSHP2 system	+ 0.5	Min NPC	0.62	1	57,742	32.8	192
			EW	0.7	1	57,834	32.4	206
			Min LGE	0.82	1	58,178	32.3	225
		Base case	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
- 0.5		Min NPC	0.58	1	62,902	40.1	173	
		EW	0.68	1	63,008	39.6	191	
		Min LGE	0.78	1	63,264	39.5	207	
Brisbane	HGSHP1 system	+ 0.5	Min NPC	0.36	0.36	39,936	51.1	90
			EW	0.54	0.56	40,794	45.1	126
			Min LGE	0.9	0.9	44,579	43.3	186
		Base case	Min NPC	0.34	0.34	41,125	55.4	84
			EW	0.56	0.56	42,070	49.1	126
			Min LGE	0.9	0.9	45,798	47.6	181
		- 0.5	Min NPC	0.28	0.28	42,744	62.2	73
			EW	0.52	0.52	43,847	54.9	122
			Min LGE	0.9	0.9	47,332	53	175
	HGSHP2 system	+ 0.5	Min NPC	0.56	0.6	44,027	44.2	130
			EW	0.64	0.7	44,178	43.5	144
			Min LGE	0.8	0.92	44,874	43.2	171
		Base case	Min NPC	0.56	0.56	45,403	48.7	126
			EW	0.68	0.7	45,635	47.8	147
			Min LGE	0.84	0.92	46,409	47.6	174
- 0.5		Min NPC	0.56	0.56	47,509	53.9	129	
		EW	0.7	0.7	47,661	53.2	150	
		Min LGE	0.88	0.88	48,013	53	173	
Cairns	HGSHP1 system	+ 0.5	Min NPC	1	0.46	63,159	87.2	173
			EW	1	0.64	63,911	80.1	216
			Min LGE	1	0.94	66,870	77.9	264
		Base case	Min NPC	1	0.38	66,121	99.6	152
			EW	1	0.6	67,052	89.6	211
			Min LGE	1	0.92	70,337	86.9	266
		- 0.5	Min NPC	0.58	0.22	69,184	119.4	98
			EW	1	0.52	70,642	102.4	197
			Min LGE	1	0.92	74,987	98.3	272
	HGSHP2 system	N/A						

Location	Category	CoPs of RCAC	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Hobart	HGSHP1 system	+ 0.5	Min NPC	0.3	0.46	59,513	18.1	147
			EW	0.5	0.76	60,409	16.2	215
			Min LGE	0.78	1	63,377	15.5	274
		Base case	Min NPC	0.24	0.36	61,073	20	119
			EW	0.46	0.7	62,166	17.7	197
			Min LGE	0.78	1	65,650	17	267
		- 0.5	Min NPC	0.08	0.12	62,462	23.4	41
			EW	0.36	0.54	63,777	19.9	158
			Min LGE	0.76	1	68,298	18.8	254
	HGSHP2 system	+ 0.5	Min NPC	0.64	1	59,725	16.9	249
			EW	0.72	1	60,595	15.8	264
			Min LGE	0.84	1	62,742	15.5	284
		Base case	Min NPC	0.64	1	61,973	18.3	242
			EW	0.72	1	62,866	17.3	257
			Min LGE	0.84	1	65,011	16.9	276
- 0.5		Min NPC	0.64	1	64,820	20.1	233	
		EW	0.72	1	65,742	19.1	248	
		Min LGE	0.84	1	67,882	18.7	266	
Melbourne	HGSHP1 system	+ 0.5	Min NPC	0.48	0.72	65,306	98.6	200
			EW	0.64	0.96	66,298	92.2	241
			Min LGE	0.92	1	69,414	90.4	288
		Base case	Min NPC	0.44	0.66	67,793	109.8	183
			EW	0.62	0.92	68,827	102	230
			Min LGE	0.92	1	72,166	100	282
		- 0.5	Min NPC	0.36	0.54	70,776	125.8	152
			EW	0.56	0.84	71,623	115.2	209
			Min LGE	0.9	1	75,380	112.1	270
	HGSHP2 system	+ 0.5	Min NPC	0.56	1	63,435	89.4	222
			EW	0.2	0.8	66,772	86.9	96
			Min LGE	0	0.9	82,119	85	117
		Base case	Min NPC	0.52	1	66,080	98.2	206
			EW	0.18	0.66	68,779	92	84
			Min LGE	0	0.9	82,604	86	118
- 0.5		Min NPC	0.48	1	69,313	108.7	188	
		EW	0.14	0.46	71,384	96.9	63	
		Min LGE	0	0.88	83,047	87.3	119	

Location	Category	CoPs of RCAC	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Perth	HGSHP1 system	+ 0.5	Min NPC	0.36	0.38	48,095	45.8	115
			EW	0.54	0.56	49,144	41.6	156
			Min LGE	0.88	0.9	53,362	40.5	215
		Base case	Min NPC	0.34	0.36	49,583	50	106
			EW	0.52	0.54	50,603	45.7	147
			Min LGE	0.86	0.88	54,791	44.5	207
		- 0.5	Min NPC	0.3	0.32	51,341	55.5	92
			EW	0.5	0.52	52,450	50.7	138
			Min LGE	0.84	0.86	56,618	49.5	197
	HGSHP2 system	+ 0.5	Min NPC	0.44	0.64	52,396	41.4	133
			EW	0.56	0.82	52,581	40.5	159
			Min LGE	0.68	1	53,111	40.2	182
		Base case	Min NPC	0.44	0.6	54,104	45.3	129
			EW	0.58	0.8	54,379	44.4	159
			Min LGE	0.72	1	55,013	44.2	184
- 0.5		Min NPC	0.46	0.58	56,222	49.9	129	
		EW	0.58	0.74	56,514	49.4	154	
		Min LGE	0.76	0.98	57,341	49.3	186	
Sydney	HGSHP1 system	+ 0.5	Min NPC	0.36	0.38	38,779	46.7	87
			EW	0.56	0.6	39,664	41.4	124
			Min LGE	0.9	0.92	42,966	39.9	174
		Base case	Min NPC	0.32	0.32	39,917	51.8	76
			EW	0.54	0.54	40,780	45.7	117
			Min LGE	0.88	0.9	43,944	43.9	167
		- 0.5	Min NPC	0.26	0.24	41,195	58.4	61
			EW	0.54	0.5	42,338	50.7	113
			Min LGE	0.9	0.86	45,591	48.8	164
	HGSHP2 system	+ 0.5	Min NPC	0.6	0.64	42,706	40.3	131
			EW	0.7	0.76	42,848	39.9	147
			Min LGE	0.84	0.94	43,397	39.8	167
		Base case	Min NPC	0.6	0.6	43,963	44.3	127
			EW	0.68	0.7	44,020	44	140
			Min LGE	0.82	0.86	44,514	43.8	160
- 0.5		Min NPC	0.62	0.58	45,501	49.2	126	
		EW	0.74	0.7	45,677	48.9	143	
		Min LGE	0.84	0.82	46,143	48.8	158	

Effect of changes in emission factors

Location	Category	Emission factors	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Adelaide	HGSHP1 system	1.00x EF	Min NPC	0.44	0.48	57,644	38.6	148
			EW	0.6	0.66	58,365	36.3	183
			Min LGE	0.84	0.92	60,782	35.6	222
		0.75x EF	Min NPC	0.44	0.48	57,644	29.4	148
			EW	0.58	0.64	58,200	27.9	179
			Min LGE	0.82	0.9	60,565	27.3	219
		0.50 EF	Min NPC	0.44	0.48	57,644	20.3	148
			EW	0.58	0.64	58,200	19.3	179
			Min LGE	0.78	0.86	60,134	19	213
	0.25 EF	Min NPC	0.44	0.48	57,644	11.1	148	
		EW	0.56	0.62	58,068	10.7	175	
		Min LGE	0.72	0.78	59,504	10.6	204	
	HGSHP2 system	1.00x EF	Min NPC	0.6	1	60,047	36	183
			EW	0.7	1	60,160	35.6	201
			Min LGE	0.8	1	60,438	35.5	216
		0.75x EF	Min NPC	0.6	1	60,047	27.9	183
			EW	0.7	1	60,160	27.4	201
			Min LGE	0.82	1	60,502	27.2	219
0.50 EF		Min NPC	0.6	1	60,047	19.9	183	
		EW	0.7	1	60,160	19.1	201	
		Min LGE	0.84	1	60,567	18.9	222	
0.25 EF	Min NPC	0.6	1	60,047	11.8	183		
	EW	0.72	1	60,206	10.8	204		
	Min LGE	0.86	1	60,633	10.6	225		
Brisbane	HGSHP1 system	1.00x EF	Min NPC	0.34	0.34	41,125	55.4	84
			EW	0.56	0.56	42,070	49.1	126
			Min LGE	0.9	0.9	45,798	47.6	181
		0.75x EF	Min NPC	0.34	0.34	41,125	41.9	84
			EW	0.56	0.56	42,070	37.3	126
			Min LGE	0.88	0.88	45,571	36.2	178
		0.50 EF	Min NPC	0.34	0.34	41,125	28.5	84
			EW	0.54	0.54	41,907	25.6	123
			Min LGE	0.82	0.84	45,145	24.8	169
	0.25 EF	Min NPC	0.34	0.34	41,125	15	84	
		EW	0.54	0.54	41,907	13.6	123	
		Min LGE	0.76	0.78	44,446	13.3	160	
	HGSHP2 system	1.00x EF	Min NPC	0.56	0.56	45,403	48.7	126
			EW	0.68	0.7	45,635	47.8	147
			Min LGE	0.84	0.92	46,409	47.6	174
		0.75x EF	Min NPC	0.56	0.56	45,403	37.2	126
			EW	0.68	0.7	45,635	36.4	147
			Min LGE	0.84	0.9	46,258	36.2	172
0.50 EF		Min NPC	0.56	0.56	45,403	25.6	126	
		EW	0.68	0.7	45,635	25	147	
		Min LGE	0.84	0.9	46,258	24.7	172	
0.25 EF	Min NPC	0.56	0.56	45,403	14.1	126		
	EW	0.68	0.7	45,635	13.5	147		
	Min LGE	0.88	0.96	46,477	13.3	179		

Location	Category	Emission factors	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)	
Cairns	HGSHP1 system	1.00x EF	Min NPC	1	0.38	66,121	99.6	152	
			EW	1	0.6	67,052	89.6	211	
			Min LGE	1	0.92	70,337	86.9	266	
		0.75x EF	Min NPC	1	0.38	66,121	75.2	152	
			EW	1	0.6	67,052	67.8	211	
			Min LGE	1	0.92	70,337	65.8	266	
		0.50 EF	Min NPC	1	0.38	66,121	50.9	152	
			EW	1	0.6	67,052	46.1	211	
			Min LGE	1	0.9	70,133	44.8	263	
	0.25 EF	Min NPC	1	0.38	66,121	26.5	152		
		EW	1	0.58	66,892	24.4	207		
		Min LGE	1	0.86	69,721	23.8	258		
		HGSHP2 system	1.00x EF			N/A			
	Hobart	HGSHP1 system	1.00x EF	Min NPC	0.24	0.36	61,073	20	119
				EW	0.46	0.7	62,166	17.7	197
Min LGE				0.78	1	65,650	17	267	
0.75x EF			Min NPC	0.24	0.36	61,073	15.5	119	
			EW	0.46	0.7	62,166	13.9	197	
			Min LGE	0.74	1	65,188	13.4	260	
0.50 EF			Min NPC	0.24	0.36	61,073	11	119	
			EW	0.44	0.66	61,997	10.1	191	
			Min LGE	0.7	1	64,728	9.9	253	
0.25 EF		Min NPC	0.24	0.36	61,073	6.5	119		
		EW	0.38	0.58	61,560	6.3	172		
		Min LGE	0.52	0.8	62,734	6.3	214		
HGSHP2 system		1.00x EF	Min NPC	0.64	1	61,973	18.3	242	
			EW	0.72	1	62,866	17.3	257	
			Min LGE	0.84	1	65,011	16.9	276	
		0.75x EF	Min NPC	0.64	1	61,973	14.9	242	
			EW	0.74	1	63,187	13.6	260	
			Min LGE	0.86	1	65,394	13.4	279	
		0.50 EF	Min NPC	0.64	1	61,973	11.4	242	
			EW	0.74	1	63,187	10.1	260	
			Min LGE	0.86	1	65,394	9.8	279	
	0.25 EF	Min NPC	0.64	1	61,973	8	242		
		EW	0.74	1	63,187	6.6	260		
		Min LGE	0.86	1	65,394	6.3	279		

Location	Category	Emission factors	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)	
Melbourne	HGSHP1 system	1.00x EF	Min NPC	0.44	0.66	67,793	109.8	183	
			EW	0.62	0.92	68,827	102	230	
			Min LGE	0.92	1	72,166	100	282	
		0.75x EF	Min NPC	0.44	0.66	67,793	82.9	183	
			EW	0.62	0.92	68,827	77.2	230	
			Min LGE	0.9	1	71,945	75.7	279	
		0.50 EF	Min NPC	0.44	0.66	67,793	56.1	183	
			EW	0.6	0.9	68,633	52.5	226	
			Min LGE	0.86	1	71,496	51.4	273	
	0.25 EF	Min NPC	0.44	0.66	67,793	29.2	183		
		EW	0.6	0.9	68,633	27.6	226		
		Min LGE	0.82	1	71,044	27.1	267		
	HGSHP2 system	1.00x EF	Min NPC	0.52	1	66,080	98.2	206	
			EW	0.18	0.66	68,779	92	84	
			Min LGE	0	0.9	82,604	86	118	
		0.75x EF	Min NPC	0.52	1	66,080	75.6	206	
			EW	0.58	1	66,133	75.5	221	
			Min LGE	0.66	1	66,338	75.3	239	
0.50 EF		Min NPC	0.52	1	66,080	53.1	206		
		EW	0.66	1	66,338	51.5	239		
		Min LGE	0.78	1	68,737	51.2	261		
0.25 EF		Min NPC	0.52	1	66,080	30.5	206		
		EW	0.66	1	66,338	27.7	239		
		Min LGE	0.84	1	69,928	27	270		
Perth		HGSHP1 system	1.00x EF	Min NPC	0.34	0.36	49,583	50	106
				EW	0.52	0.54	50,603	45.7	147
				Min LGE	0.86	0.88	54,791	44.5	207
	0.75x EF		Min NPC	0.34	0.36	49,583	37.9	106	
			EW	0.52	0.54	50,603	34.8	147	
			Min LGE	0.82	0.84	54,294	33.9	201	
	0.50 EF		Min NPC	0.34	0.36	49,583	25.9	106	
			EW	0.5	0.52	50,403	23.9	143	
			Min LGE	0.78	0.8	53,792	23.4	194	
	0.25 EF	Min NPC	0.34	0.36	49,583	13.8	106		
		EW	0.48	0.5	50,217	13	139		
		Min LGE	0.68	0.7	52,524	12.8	178		
	HGSHP2 system	1.00x EF	Min NPC	0.44	0.6	54,104	45.3	129	
			EW	0.58	0.8	54,379	44.4	159	
			Min LGE	0.72	1	55,013	44.2	184	
		0.75x EF	Min NPC	0.44	0.6	54,104	35.2	129	
			EW	0.58	0.8	54,379	34	159	
			Min LGE	0.72	1	55,013	33.7	184	
0.50 EF		Min NPC	0.44	0.6	54,104	25.2	129		
		EW	0.58	0.8	54,379	23.6	159		
		Min LGE	0.74	1	55,103	23.2	188		
0.25 EF		Min NPC	0.44	0.6	54,104	15.1	129		
		EW	0.58	0.8	54,379	13.2	159		
		Min LGE	0.76	1	55,196	12.7	191		

Location	Category	Emission factors	Reference point	Alpha	Beta	NPC (\$)	LGE (ton CO _{2e})	GHE Length (m)
Sydney	HGSHP1 system	1.00x EF	Min NPC	0.32	0.32	39,917	51.8	76
			EW	0.54	0.54	40,780	45.7	117
			Min LGE	0.88	0.9	43,944	43.9	167
		0.75x EF	Min NPC	0.32	0.32	39,917	39.2	76
			EW	0.54	0.54	40,780	34.7	117
			Min LGE	0.86	0.88	43,749	33.4	164
		0.50 EF	Min NPC	0.32	0.32	39,917	26.6	76
			EW	0.54	0.54	40,780	23.7	117
			Min LGE	0.82	0.86	43,495	22.8	160
	0.25 EF	Min NPC	0.32	0.32	39,917	14	76	
		EW	0.52	0.52	40,634	12.7	114	
		Min LGE	0.8	0.84	43,256	12.3	158	
	HGSHP2 system	1.00x EF	Min NPC	0.6	0.6	43,963	44.3	127
			EW	0.68	0.7	44,020	44	140
			Min LGE	0.82	0.86	44,514	43.8	160
		0.75x EF	Min NPC	0.6	0.6	43,963	33.9	127
			EW	0.7	0.72	44,065	33.5	143
			Min LGE	0.86	0.9	44,643	33.3	165
0.50 EF		Min NPC	0.6	0.6	43,963	23.6	127	
		EW	0.72	0.74	44,115	23	146	
		Min LGE	0.88	0.92	44,710	22.9	167	
0.25 EF	Min NPC	0.6	0.6	43,963	13.2	127		
	EW	0.72	0.74	44,115	12.6	146		
	Min LGE	0.88	0.92	44,710	12.4	167		