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Addressing Sustainability in Ground Source Heat Pump Projects

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ABSTRACT

The use of ground source heat pump (GSHP) systems (also referred to as shallow geothermal or geo-exchange) is increasingly being considered as an energy efficiency measure to service varied heating and cooling loads. Such systems have the potential to provide carbon emission reduction and cost savings relative to traditional heating and cooling plant, due to their superior energy efficiency. A GSHP system comprises three key elements:

1. The thermal load: the building or process heating and/or cooling demand that results in a serviceable thermal load;
2. The heat transfer system: the plant; comprising heat pumps, heat exchangers and associated controls; and
3. The thermal sink and/or source: the receiving environment coupled to the heat transfer system via a ground collector (typically a horizontal loop, abstraction and recharge bores or borehole heat exchangers (BHE)).

While the underpinning technology is not new, best practice in design is still evolving. One challenge in GSHP projects that requires attention is sustainability, for which clear targets do not currently exist. While sustainability must address short and long-term considerations for the water resources of the area, a true assessment of sustainability requires the wider system beyond hydrogeological elements to be assessed. To determine if a GSHP system can be considered sustainable, a series of tests are proposed:

1. Can the peak thermal loads be serviced by the receiving environment within the boundaries of the site?
2. Will there be an unacceptable change in the receiving environment or to any thermally sensitive receptors due to the long-term operation of the system?
3. Will the system operate in the long-term as intended, to maintain economic and environmental feasibility for the design life of the system?

In particular, temperature change resulting from GSHP system operation (referred to herein as thermal interference) and water quality impacts, require specialist assessment. While these tests may appear obvious to an accredited or experienced GSHP designer, they may be less obvious to others, including traditional HVAC designers and installers, or hydrogeologists who are not familiar with GSHP technology. A suitable framework for assessing sustainability should be capable of meeting the needs of GSHP designers, the wider HVAC project team as well as the regulators.

1. INTRODUCTION

In an increasingly carbon constrained world, systems that maximize the efficient use of available resources while being financially beneficial, will continue to gain market share over traditional technology. In the case of servicing thermal loads, Ground Source Heat Pump (GSHP) technology which offers greater energy efficiency over traditional heating and cooling plant, continues to become increasingly relevant to development and industry.

In the US, energy use in residential, commercial and institutional buildings account for about 40% of the primary energy consumption and carbon emissions, over 73% of the electricity consumption, 55% of natural gas consumption and significant oil consumption. Of these total energy uses, the thermal loads of these buildings that could potentially be serviced by a GSHP system (i.e. from space heating, space cooling, water heating and refrigeration) accounts for up to 63% of energy use (DOE, 2010).

GSHP technology provides significant potential to reduce these energy uses and improve environmental performance of buildings as well as some industrial processes. As the cost of heating and cooling increases, due to climate change and the rising charges for fuel, any opportunity reduce costs should be explored.

The number and capacity of GSHP systems installed worldwide is uncertain and has been estimated by various authors. What is clear however, is that the market has grown significantly. Le Feuvre and Kummert (2008) estimated growth exceeding 10% annually over the years from 1998 to 2008, with most growth in the US and Europe, though other countries such as Japan and Turkey were showing significant growth. This has been driven by a need to reduce peak cooling loads in urban areas and the proliferation of agriculture in glass houses for each country respectively.

Lund *et. al*. (2004) estimated there to be 1,100,000 GSHP units installed globally in 2004, with a total estimated capacity of 12,000 MWt (thermal Megawatts), with an annual energy use of 72,000 TJ (Terrajoules) or 20,000 GWh (Gigawatt hours). These estimates were updated by Goetzler *et. al.* (2009) for the US Department of Energy GSHP market overview, giving a global installed capacity of 15,4000 MWt, of which about 56% was installed in the US.

Despite this activity in installation, the relatively rapid expansion of GSHP technology has resulted in best-practice in design and specification being poorly defined and poorly regulated in many jurisdictions. Whilst many of the relevant hydrogeological analysis techniques are commonly understood, techniques for assessing wider aspects of the system are still developing and are not as widely applied in GSHP projects.

2. GROUND SOURCE HEAT PUMP SYSTEMS

GSHP technology does not involve novel or new plant. The technology within the heat pump unit is substantially similar to other forms of heat pump and heat exchanger. The distinguishing element of a GSHP system is the receiving environment that acts as the thermal sink and/or source and the methodology for coupling this to the GSHP unit, (i.e. the receiving environment is the ground beneath the site and the coupling methodology is the ground collector by which thermal energy is sourced from or rejected into it. Types of ground collector are discussed further later in this section).

Higher efficiency from GSHP systems over air source heat pump systems is achieved as a result of coupling the heat pump with the ground. The ground, beneath a shallow zone of daily and seasonal temperature change has significantly more stable thermal conditions than the atmosphere. The temperature of the ground is typically the average annual air temperature, with the exception of active geothermal areas such as Taupo and Rotorua, where a GSHP system may not be the most suitable option.

Figure 1 is a comparison of the annual cycle of air temperature and ground temperature (at various depths) for a site in Melbourne, Australia. This shows how the stable ground temperature will be cooler than the surface air temperature in the summer months, so heat can be rejected to the ground. Conversely, in winter the ground will be warmer than surface air temperature, and can be used as a heat source. This natural seasonal thermal gradient is the opposite of that exploited by air source heat pumps and is the reason that GSHP operate at a higher efficiency.

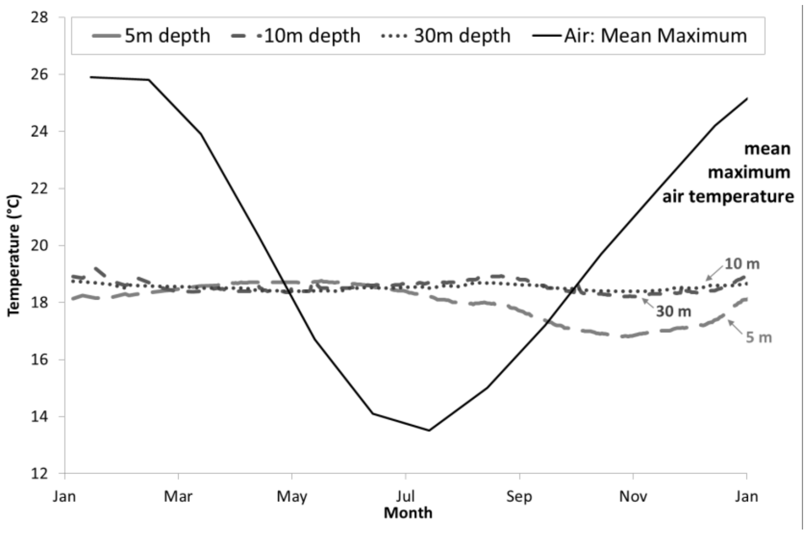

Figure 1: Annual temperature fluctuations recorded at a single site in Melbourne, Australia of mean maximum air temperature with the temperature recorded at 5 m, 10 m and 30 m below ground level.

GSHP systems are categorized into two principal types: open loop and closed loop. Open-loop systems (Figure 2) pump groundwater from the ground to the surface. The groundwater is then passed through a heat transfer system, before being disposed of (at a different temperature than before; warmer when the system is used for cooling, or colder when the system is used for heating) either to waste or by injection back into the ground.

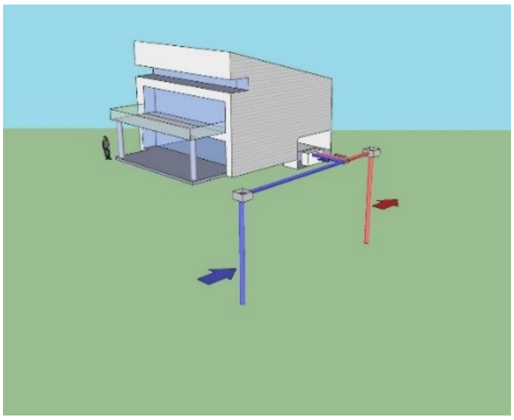

Figure 2: Schematic of an Open Loop Ground Source Heat Pump System where water is sourced from an abstraction borehole, then recharged back to the source aquifer via an injection borehole (shown here in cooling mode).

By contrast, closed-loop systems (Figure 3) do not abstract groundwater, but instead circulate a fluid through a loop of borehole heat exchange (BHE) pipes buried in the ground. The circulating fluid passes through a heat transfer system at the surface, before being recirculated back through the buried ground loop, to exchange heat with the surrounding soil or rock.

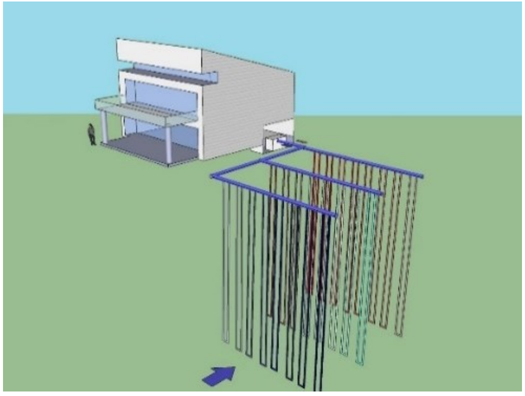

Figure 3: Schematic of a Closed Loop Ground Source Heat Pump System where fluid is circulated through a closed loop buried in the ground. Here thermal energy is exchanged with the ground via conduction and/or convention.

As thermal energy is exchanged with the receiving environment, both GSHP systems will inevitably have some thermal impact on the receiving environment. A closed loop system requires no abstraction or injection of water, and so there is no direct hydraulic impact from operation of the system. The drilling and installation however can have an impact on the hydraulic behavior of the receiving environment. These two forms of impact, thermal and hydraulic are discussed further in the following section.

3. DEFINING SUSTAINABILITY FOR GROUND SOURCE HEAT PUMP SYSTEMS

For the purposes of this paper, the author proposes the following definition of sustainability with respect to an individual GSHP system: "the ability to operate within acceptable efficiency and performance parameters throughout the design life of the system without adversely affecting any other temperature sensitive receptors".

It is acknowledged that individual GSHP systems do not operate in isolation, and other environmental and design factors should be assessed as part of a holistic sustainability assessment, such as minimization of the energy demand of the building. However such considerations were outside the scope of this paper.

Three proposed tests to address sustainability are summarized in Table 1. Sustainable design considerations have been summarized for an open and closed loop system individually. Where appropriate, the sustainable design considerations have been divided between hydraulic considerations (i.e. those concerned with the spatial and temporal movement of groundwater) and thermal considerations (i.e. those concerned with the movement and dissipation of thermal energy in the ground).

Table 1: Summary of the Proposed Sustainability Tests for Ground Source Heat Pump Projects

Proposed Sustainability Test	Open Loop Sustainable Design Considerations	Closed Loop Sustainable Design Considerations
Thermal sustainability: 1. Can the peak thermal load be serviced by the receiving environment within the boundaries of the site?	Hydraulic considerations: can the peak flow rate be achieved from a practical number of bores within the site without causing unacceptable levels of drawdown or recharge mounding? Thermal considerations: can the peak load be serviced by the aquifer without thermal interference between abstraction and injection bores?	Thermal considerations: can the thermal energy of the peak load be exchanged with the ground via an acceptably sized (and of practicable depth) borehole heat exchanger (BHE) borefield?
Thermal sustainability: 2. Will there be an unacceptable change in the environment or to any thermally sensitive receptors due to the long-term operation of the GSHP system?	Hydraulic considerations: can the drilling, drawdown or recharge mounding in the vicinity of the bores result in unacceptable changes to the aquifer integrity or buried structures, or result in increased risk of groundwater pollution? Thermal considerations: can the migration of thermal energy away from the site cause an unacceptable change to a temperature sensitive receptor?	Hydraulic Considerations: have the design specification, construction and installation standards been adequate to mitigate against leaks? Thermal considerations: can the migration of thermal energy away from the site cause an unacceptable change to a temperature sensitive receptor?

Proposed Sustainability Test	Open Loop Sustainable Design Considerations	Closed Loop Sustainable Design Considerations
GSHP operational optimization: 3. Will the system operate in the long-term as intended, to maintain economic and environmental feasibility for the design life of the system?	Hydraulic considerations: can the bores abstract and recharge groundwater as intended throughout the design life, or will water quality, poorly designed or maintained bores, or external factors cause loss of efficiency or operational problems Thermal considerations: where the thermal load is not balanced (i.e. unequal heating and cooling loads over an annual cycle), will an unacceptable level of thermal interference occur whereby abstracted groundwater becomes too warm or too cold for the heat pump to operate efficiently?	Hydraulic considerations: is the borefield of adequate size to allow for redundancy (i.e. the loss of individual BHE due to operation of the system)? Thermal considerations: is the borefield of adequate size to operate within acceptable thermal specifications?

Whilst many of the hydraulic aspects of these tests may appear obvious to a practicing hydrogeologist, the thermal aspects may be less obvious to the GSHP designer as well as other disciplines in the design team; hence they may be overlooked. In the author's experience, hydraulic considerations appear to be widely accepted, since the design process of GSHP systems must inevitably address geological and hydrogeological requirements of investigation and drilling. However, thermal tests regarding impacts of long-term operation and water quality are sometimes neglected, and this can lead to problems during the operational life of the systems.

4. SUSTAINABILITY ASSESSMENTS IN GROUND SOURCE HEAT PUMP SYSTEMS

Each of the proposed three tests will be discussed in further detail in the following sections.

4.1 Test 1: Thermal Sustainability: Servicing the Peak Load

Thermal sustainability is another aspect of GSHP design that is commonly overlooked. A GSHP system can be considered thermally sustainable if the level of thermal interference due to operation of the system remains at an acceptable level, i.e. it has, over the design life of the system:

1. No significant detrimental impact on the efficient operation of the GSHP system itself (i.e. where the thermal resource in the ground is maintained at a level that does not significantly reduce the efficiency of the GSHP system in the long-term);
2. No significant detrimental impact on other temperature sensitive receptors (e.g. other local GSHP systems or groundwater dependent ecosystems).

The importance of ensuring thermal sustainability for the design life of the system at the design stage of the project is critical to a successful GSHP system, especially as unacceptable levels of thermal interference may not be readily observable for a number of years after the GSHP system has been installed and commissioned. Retrofitting additional HVAC plant or recovering the thermal resource of the ground is a lengthy and expensive task.

Thermal sustainability therefore should be demonstrated prior to the detailed design of the GSHP system, to understand the risk of thermal interference occurring during the design life of the system.

The peak load is determined by the thermal performance of the building or industrial process. Unlike traditional HVAC plant, servicing the peak load is only part of designing the GSHP system. The peak load of the building may not be the same as the peak load serviced by the GSHP. Less capital intensive ways of servicing a load may be possible by dividing the load between a GSHP system and traditional supplementary heating and cooling plant. This is discussed further in Section 4.3 Test 3: Ground Source Heat Pump Optimization.

Assuming the peak load has been optimized to maximize financial performance, Test 1 is concerned with assessing whether the peak thermal exchange is achievable within the footprint of the site. Large loads applied to open loop systems may require large volumes of water to pass the heat exchangers, necessitating either a large volume of groundwater to be extracted and disposed of, or in closed loop systems a large number of BHE may be required to achieve sufficient heat exchange capacity.

In situations where the peak load is deemed too large to service by GHSP system alone, an open loop system is unlikely to be viable, either because it is not practicable to fit sufficient boreholes onto site, or because the cost of the boreholes is excessive compared to alternative solutions. For closed loop systems, the footprint of the BHE borefield may be too large to fit within the site, or be cost prohibitive.

Breaking the system down into the key elements of source, heat transfer system and load can help identify potential modifications to the design to make the system sustainable. Each is discussed individually in further detail in the following sections.

4.1.1 Modify the source

Changes to the borehole design, construction and development could increase its thermal capacity, thereby reducing the required number of boreholes. In practice, the constraints of the hydrogeological or thermal characteristics beneath the site are likely to put an upper limit on the peak thermal capacity of the receiving environment.

4.1.2 Modify the heat transfer system

The selection of alternative plant (heat pump or heat exchanger) and its or operational characteristics may offer a small opportunity to improve performance, e.g. selecting a heat pump that has a wider peak operational temperature range or increasing the allowable temperature change across the heat exchanger.

4.1.3 Modify the load

Perhaps the most effective way that the peak groundwater flow rate can be reduced is to consider reducing the load applied to the GSHP system. One approach is to use a hybrid system in which a relatively constant baseload (of less than 100% of the peak heating/cooling load) is applied to the GSHP system, with the remaining short-term peaks above the baseload dealt with by supplementary traditional heating/cooling systems. The size of the GSHP system required will therefore be reduced. Even considering for the cost of the supplementary heating and cooling systems, this will still allow significant reductions in energy costs and carbon dioxide emissions to be achieved, while substantially reducing capital costs compared to the case where the entire building load is applied to the GSHP system. This is discussed further in Section 4.3 Test 3: Ground Source Heat Pump Optimization.

4.2 Test 2: Thermal Sustainability: Long-term Thermal Interference

Younger (2014) notes that the typically high levels of thermal insulation demanded by modern building regulations, and the presence heat sources such as desktop computers, results in many commercial office buildings requiring minimal space heating, even in winter. However, from a thermal sustainability view point, it is simpler to develop systems that are seasonally balanced; that is, those in which a summer cooling demand is at least approximately balanced by a winter heating demand. In such balanced systems, there is little or no net change in the temperature of the receiving environment. Where this imbalance exists, long-term thermal interference will need to be addressed.

It follows that an imbalanced annual load will result in a bias of either heating the receiving environment (in the case of an excess of cooling requirement) or cooling down of the receiving environment (in the case of an excess of heating requirement). Due to the large thermal mass of the ground and relatively low thermal dissipation or replenishment, this net temperature change can build up over many years until unacceptable levels of heating or cooling the receiving environment has occurred (i.e. thermal interference). As with other anthropogenic impacts on the environment, adverse thermal interference can be observed in any receptor that is sensitive to change. In the case of thermal interference, this includes groundwater dependent ecosystems and other groundwater abstractors. Perhaps most likely tends to be an unacceptable level of thermal interference on a GSHP system due to its own operation, as a result of a self-imposed feedback loop, for example between abstraction and re-injection wells in an open loop system.

Beyond the site boundary, the problems associated with thermally over-exploiting an area has been documented in a number of locations. Ferguson and Woodbury (2006) reported on thermal interference due to the number and proximity of GSHP systems in Winnipeg, Canada. They concluded that the current observed temperatures in the receiving environment (the Carbonate rock aquifer beneath Winnipeg), indicated that the GSHP cooling systems were unsustainable and inefficient due to excessive thermal interference.

Already, the body responsible for licensing of groundwater abstractions in England and Wales, the Environment Agency (EA), has raised concerns that the use of large-scale GSHP systems may have a significant impact on available thermal and groundwater resource of London (Fry, 2008).

Commonly, best practice in determining long-term sustainability of scheme will include testing and possibly thermal modelling to be undertaken by the applicant (EA, undated). Thermal modelling requires the use of specialist software. For larger open loop systems, it may require numerical modelling of coupled groundwater flow and heat transport modelling using software such as Feflow, by DHI WASY. Closed loop systems may be designed by proprietary software packages such as Earth Energy Designer (EED) or Ground Loop Design (GLD). When appropriately used, these software should provide predictive simulations of the behavior of the ground loop and receiving environment for the design life of the system. As well as providing information on the thermal interference, these software also provide information for the optimization of the system.

4.3 Test 3: Ground Source Heat Pump Operational Optimization

GSHP operational optimization involves maximizing the environmental and financial benefit by considering the sizing of the plant and ground loop in conjunction with the operational regime. The operational regime must include detailed analysis of the spatial and temporal distribution of the thermal load and how this can sustainably and most efficiently be serviced, potentially by a combined GSHP and traditional HVAC plant.

GSHP operational optimization requires a specialist knowledge that crosses traditionally disparate disciplines of hydrogeology and building services. Often this step is overlooked altogether, which has significant implications for the efficiency of the GSHP system.

In the author’s experience, most GSHP projects larger than single domestic installations become more financially viable if the baseload can serviced by a GSHP system with larger peaks being serviced by traditional HVAC plant. The division of the baseload and peak is not intuitive with respect to financial and operational optimization and careful analysis of the loads is necessary to ensure this is achieved.

In additional to servicing a baseload, simultaneous heating and cooling must be considered in the design. This improves the efficiency of the GSHP system by utilizing excess thermal energy in one part of the development use reusing it or storing it for later re-use (e.g. excess coolth can be stored as ice, to be used at a later time when there is a cooling demand).

Integration with other renewable technology is also often overlooked. Combining a GSHP system with other technologies, such as solar thermal, can maximize the efficiency of both systems by moving or storing excess thermal energy when it would otherwise be left unutilized.

5.0 CONCLUSIONS

The increasing application of GSHP systems, especially in urban areas, will set new sustainability challenges for designers and regulators. Hydrogeological analysis, such as that undertaken by the EA (undated) shows that open loop systems relying on aquifer re-injection to dispose of wastewater may suffer from thermal breakthrough, negating many of the potential long-term benefits of groundwater energy systems. Similarly, if injected warmer/colder water migrates off site, it may affect the efficiency of neighboring open loop systems; some evidence of this is reported by Ferguson and Woodbury (2006).

It is possible that in the future thermal interference between neighboring systems may become a significant factor in design, operation and regulation of open and potentially closed loop systems. If large numbers of major buildings in urban areas are to have GSHP systems, then sustainability tests such as those described in the paper will become an accepted part of the design process. It may be that successful implementation of open loop systems on neighboring urban sites may require approaches such as hybrid systems (where the building baseload is applied to a groundwater system, supplemented by traditional systems at times of peak load), and on aquifer thermal energy storage (where groundwater is used to provide both heating and cooling, balanced on a seasonal basis) or combining the systems, to work in combination with each other, such as in a district energy system.

If sustainability issues are not appropriately addressed, then there is a risk that some GSHP systems may 'fail' before the end of their design life. Failure may take several forms, including: unacceptable thermal interference; off-site migration of warmer/colder water affecting neighboring sites; and/or impact on groundwater resources (such as excessive aquifer drawdown). Due to the nature of thermal interference potentially not occurring for many years after commissioning, it is likely that the prevalence or otherwise of failures will not become known until systems have been in operation for several years at least. This poses significant risks to developers and contractors, given the liability and expense of retrofitting or recovery of poorly operating GHSP systems.

A final aspect of sustainable design that is often overlooked is what happens when the building is in use. Building industry guidance highlights the need for effective in-use energy management and for post occupancy evaluation, to determine whether the building and the GSHP system perform as intended and meet the user's needs. The availability of post-occupancy information should provide feedback on the sustainability of current designs, and will allow development of further sustainability tests for open loop systems.

REFERENCES

DOE, 2010. U.S. Department of Energy, Annual Energy Outlook 2010. Energy Information Administration; Buildings Energy Data Book: http://btscoredatabook.eren.doe.gov/default.aspx, website accessed May 2014.

EA, Undated. Environment Agency. Environmental good practice guide for ground source heating and cooling. Version 3. EA Reference: GEHO0311BTPA-E-E.

Ferguson, G., Woodbury, A. D., 2006. Observed Thermal Pollution and Post-development Simulations of Low-temperature Geothermal Systems in Winnipeg, Canada. Hydrogeology Journal November 2006, Volume 14, Issue 7, pp 1206-1215

Fry, V.A., 2009. Lessons from London: regulation of open-loop ground source heat pumps in Central London. Quarterly Journal of Engineering Geology and Hydrogeology 2009; v. 42; p. 325-334

Goetzler, W., *et. al.*, 2009. Navigant Consulting Inc. Ground Source Heat Pumps: Overview of Market Status, Barriers to Adoption, and Options for Overcoming Barriers. U.S. Department of Energy, Energy Efficiency and Renewable Energy Geothermal Technologies Program.

Le Feuvre, P., Kummert, M., 2008. Ground Source Heat Pumps in the UK – Market Status and Evaluation. Proceedings of the 9th annual IEA Heat Pump Conference.

Lund, J., Sanner, B., Rybach, L., Curtis, R., and Hellström, G.: Geothermal (Ground-Source) Heat Pumps a World Overview. GHC Bulletin, (September 2004).

Younger, P.L., 2014. Hydrogeological challenges in a low-carbon economy. Quarterly Journal of Engineering Geology and Hydrogeology 2014, v.47; p7-27.