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A First for India – 100 kW Borehole Based Geothermal Heat Pump System for Space Heating in the Himalayas

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ABSTRACT

With increasing concerns surrounding the availability, cost and logistics of supplying heating oil to remote research establishments, the Indian Defence Research & Development Organisation (DRDO) has initiated the first significant closed loop GSHP project for space heating application in India. A pilot project was undertaken by the Snow & Avalanche Study Establishment (SASE), a R&D establishment under DRDO, for installation of a 100kW space heating system near Manali in Himachal Pradesh. In this project, the installation of a test bore hole and a Thermal Response Test (TRT) was conducted, before the rest of the closed loop borehole field was developed.

The ground loop array is connected to a reverse cycle water-to-water heat pump that primarily delivers heating to buildings on the site, as well as possible provision of supplementary cooling to the cold laboratories that form part of the research establishment. A significant element in the evolution of this installation was the procurement of all of the borehole field materials from Indian manufacturers and suppliers.

By using locally sourced hydropower generated in the region, this technology will offer security of supply and a significant reduction in CO_2 emissions compared to the existing oil fired installation. Following evaluation of this pilot project, the Indian DRDO expects to make use of GSHP technology at other research sites in their property portfolio, particularly for space heating and cooling requirements. The installation is also increasing the general awareness of the potential for GSHP systems in the wider region.

1. INTRODUCTION

With the second largest population in the world, and a rapidly growing economy, it is recognised that the newly elected (2014) Prime Minister of India has the delivery of adequate and affordable energy supplies high on his agenda. In much of the northern area, heating is currently delivered using oil or electricity. Although India has indigenous oil supplies, it is increasingly having to rely on expensive imports which adversely impact its balance of payments. Both gross and net imports of crude oil have increased from 11.68 MTs during 1970-71 to 171.73 MTs during 2011-12. Given that most of the country's electricity is generated using indigenous and imported coal, the use of direct electricity to deliver low-grade space heating is expensive both financially and in terms of carbon emissions.

With its large geographical and climatic spread, ranging from heating dominated requirements in the north, to cooling dominated requirements in the south, and a varied range of geological conditions, it is possible that ground source or geothermal heat pumps (GSHPs) will have a role to play in India. To date there has been very little GSHP activity, with a few small horizontal systems installed, and one or more larger open loop systems. There is little or no experience of larger closed loop, borehole based, systems to date.

2. SASE - MANALI

Following representations by Indian renewable energy companies with an interest in promoting GSHP systems, the head of a section of the Indian Defence Force's Research departments (DRDO) decided to move forward with a project. The Manali site of the DRDO's Snow and Avalanche Study Establishment (SASE) was selected as a suitable location for a demonstration project. The site (Figure 1) is in the Himalayan foothills, just outside the town of Manali, Himachal Pradesh, at a height of ~2000m(~6525 ft). Buildings on the site are currently heated using oil or direct use electricity. The oil has to be transported a significant distance along poor quality mountain roads. Interestingly, this mountainous region is currently seeing a significant expansion in hydroelectric generation. The use of locally generated renewable electricity to drive efficient, electric, vapour compression, heat pumps could therefore be an attractive offering in these remote mountain locations, both in terms of energy costs and in delivering significant carbon reductions. However, with the site being about fourteen hours drive from Delhi, in a remote mountainous region, the installation of a 100kW closed loop, borehole based GSHP at this location posed interesting challenges.

Following discussions with external consultants with knowledge of GSHP systems, the DRDO drew up a specification for the GSHP project and went out to tender for the delivery of a 100kW closed loop, borehole based system. The contract was awarded to Efficient Energy Systems Pvt. Ltd. of Delhi. The project was to be developed in a phased approach, and contained a detailed specification of the requirements that were to be met.

As is now common practice elsewhere in the world, a Thermal Response Test (TRT) was called for as part of the process and to allow for design purposes. This required the mobilisation of a drilling rig to site (Figure 2), the drilling of a full sized, 100m deep borehole, installation of a single U-tube and full borehole grouting. The borehole drilling and completion took place in the last quarter of 2012, and the thermal response test was carried out in December 2012. The drilling of the test hole revealed that the geology consists of riverine sediments composed of pebbles, sand, and in some case small boulders. This persisted over the entire 102m depth of the hole.

Figure 1: General view of the site. Plant room at lower left, borehole field mainly to the right hand side of the road.

Figure 2: Drilling of the borehole for the thermal response test.

The 48 hour long thermal test was undertaken using a hired TRT rig, temporarily imported from abroad. It was carried out in arduous winter conditions and had significant problems with intermittent generator operation. Although the recorded temperature response suffered from the power outages, analysts at Water Furnace did their best to extract useful data from the test. The equilibrium ground water temperature was reported as being 8.9°C. The reported thermal conductivity value lies between 5.9 and 6.4 W/mK. The higher value arises from a conventional line source analysis method, and the lower value arises from the application of the ORNL Shonder/Beck numerical method. These are high values, and may have arisen due to the operational difficulties with the test.

Following the thermal test, the drilling rig was re-mobilised to site, with a requirement to deliver 2500m of completed borehole. From the drilling of the thermal test borehole it was appreciated that because of the difficult geology, it would be necessary to case the holes to full depth. Whilst the original intention was to deliver twenty-five, 100m deep holes, drilling difficulties eventually resulted in a combination of twenty seven holes of varying depth, with a total overall borehole length of 2500 metres. The boreholes were temporarily capped and the rig de-mobilised from site in December 2013. Due to the area of the site that had been allocated for the boreholes, and some of the drilling difficulties, the final 27 borehole layout was somewhat other than "regular", but in general the borehole spacings were typically ~6 metres.

The next stage of the installation process required the sourcing of all of the ground loop pipework materials. Whilst enquiries were initially made of foreign suppliers, parallel enquiries were made of Indian manufacturers of HDPE and MDPE polyethylene pipework product. In the event, it proved possible to source all of the plastic pipework materials in India, these included:

- 100 metre, 32mm OD, HDPE, SDR-11 U-tubes.
- Custom made 110mm OD, 9 way x 32mm manifolds with flush/purge and bleed ports and 32mm isolation valves.
- Electrofusion fittings - 32mm, 63mm, 90mm including couplers, elbows and reducers.
- 90mm and 63mm MDPE header pipe.
- Custom made 110mm OD, 3 way x 110mm plant room manifolds in MDPE, with full bore butterfly isolation valves.
- Adapter flanges to go from 110mm MDPE to 2" steel pipework in plant room.
- Electrofusion welding equipment, butt fusion welding equipment and technicians.

The U-tubes and manifolds were manufactured off-site in Maharashtra State and then delivered to site by truck, a four day road journey across several Indian States. This local sourcing resulted in a significant cost saving over the use of imported materials, due to both the lower cost of Indian manufacture, and the elimination of airfreight costs and import taxes.

With the U-tubes on-site it was possible to arrange for their insertion in the boreholes, once the exposed lengths of steel casing had been cut back to the bottom of the header trenches. In the absence of a motorised reel handler, the U-tubes were unrolled on site, filled with water, and then lowered manually into each borehole. This was a relatively straightforward operation as the boreholes are fully cased to depth and no blockages were encountered. Care was taken to avoid the U-tubes being damaged on the edges of the steel casing. Each U-tube was then pressure tested and witnessed by the client to 6 bar using a locally sourced hand pressure tester (Figure 3). Having passed the pressure test, it was then possible for the grouting of the boreholes to be undertaken. In the absence of a local supply of thermally enhanced grout, sodium bentonite grout was obtained from an Indian source. This was mixed on-site with a paddle mixer and injected into each borehole using a tremie pipe and a positive displacement pump. It had been agreed with the client that only the top half of the boreholes would be grouted in order to provide hydraulic isolation. The lower half of these holes are permanently filled with groundwater at this location, which should result in enhanced heat transfer, and will compensate for the use of standard bentonite grout in the upper part of the holes.

Figure 3: Pressure testing of individual U-tube.

3. GROUND ARRAY INTERCONNECTION

Because of the difficult drilling conditions which resulted in changes to borehole locations, the final geometrical layout of the 27 boreholes posed a challenge in terms of interconnection in order to deliver balanced hydraulic flows to the individual U-tubes. As well as accommodating the non-symmetric borehole arrangement, a road had to be crossed to reach the plant room, a sub-surface Nala (drain), and an ornamental wall had to be negotiated by the header pipework. (Figure 4)

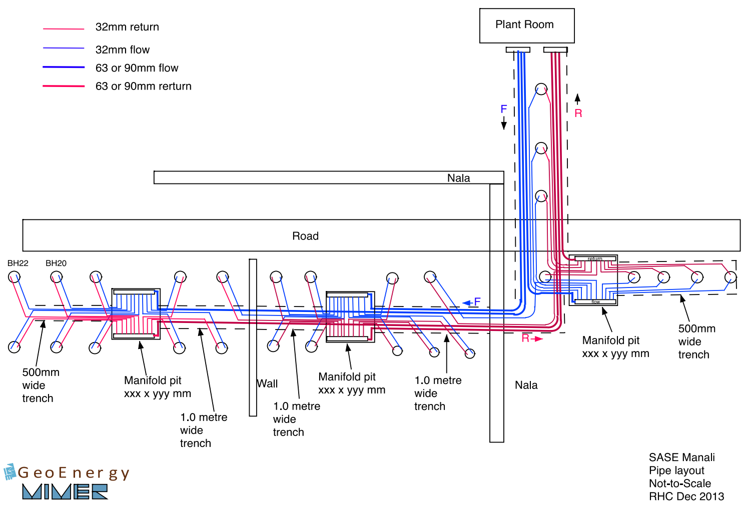

Figure 4: Schematic showing the interconnection of the borehole array.

The approach adopted was to divide the borehole field into three sections, each containing nine boreholes. In each of the three sub-arrays, the borehole U-tubes were connected to a pair (flow and return) of pre-fabricated nine way manifolds using 32mm HDPE pipe laid in trenches between each borehole location and a manifold "pit" (Figure 5). Each borehole connection (flow and return) to the manifolds was provided with a 32mm full bore isolation valve. This allows for flushing and purging of individual boreholes, thermal transfer fluid (or "TTF", viz antifreeze) injection, and future borehole isolation in the event of (an unlikely) U-tube failure.

Each of the six manifolds (three flow, three return) was provided with a valved flush and purge point, and a valved air bleed. The manifolds were laid flat in the bottom of the pit, and once all of the pipework interconnections had been made; a brick/ block surround was constructed. These three manifold pits have been covered and provided with an access manhole to allow for future inspection and/or borehole isolation.

With the manifold pits in place, a pair of flow and return headers were run from each pit back to the plant room location. These headers were run out in 90mm MDPE from the plant room, with a reduction to a 63mm run for final connection to the manifolds in the pits. With the three manifold pits being at different distances from the plant room, the ratio of 90mm to 63mm length in each header was adjusted to balance the flow to each of the three sub-arrays. The 90mm headers are connected to 110mm x 3 way manifolds at the plant room location; with full bore butterfly valves providing isolation for each of the three main circuits.

Figure 5: One of three manifold pits, showing manifolds, isolation valves and nine pairs of borehole connections.

Whilst it might have been possible to design a reverse return ("Tichelmann") layout for this site, the final manifold arrangement, provides a number of advantages on this type of project. Because of the remoteness of this location, and that fact that it was the first closed loop installation of significant size, there were limitations on the availability of commercial size flushing and purging equipment. The ability to isolate individual boreholes allows for flushing and air purging to be carried out using either a small pump attached to the manifold flush/purge points, or by using the main ground loop circulation pump - with all other manifolds and boreholes isolated. This ensures a high enough flow rate to strip micro-bubbles from the pipework and to flush debris. Once this flush and purge process had been completed, it was possible to use a hand pump to inject the required amount of pure thermal transfer fluid into each individual borehole, whilst only displacing fresh water. This eliminated any wastage of thermal transfer fluid that can arise when partial mixing occurs during injection. With control over individual boreholes, it is possible to achieve full mixing, one borehole at a time, thus avoiding the potential for stagnation arising due to a U-tube being "locked" with 100% TTF in its lower section.

The installation of the ground loop array and the header pipework, pressure testing of loops, and grouting of the boreholes was completed by late December 2013. It was fortunate that snow, which can be expected to fall at any time from late October to November onwards, did not arrive until the groundworks had been completed - an unexpected, but slightly worrying benefit of the impact of climate change in this region perhaps. Whilst water was left in lower sections of the U-tubes, no water was left in the header pipework over the ensuing winter season, thus avoiding any potential difficulty arising from freezing.

In the first quarter of 2014 arrangements were made for the shipping of the heat pump, and the location, purchase and shipment to site of other plant room equipment. The other major components were the ground loop and load side circulation pumps. With the ground loop pipework layout now in place, it was possible to size the ground loop pump to deliver the required flow rate to the heat pump, at a reasonable pressure drop. With long delivery times for the more usual integrated motor/pump assemblies, coupled motor /pump sets were sourced from a pump supplier in Delhi. Once the heat pump had cleared customs at Delhi airport, it was transported, together with the two motor/pump sets, by road to Manali. In Spring 2014, the site activity resumed to complete the plant room installation, couple the heat pump to the ground loop and a dummy load, and to commission the system. It had been agreed with the client that the system would be accepted on the basis of demonstrating that the heat pump could deliver in excess of 100kW of heat. This was to be done by raising a tank of water to the maximum temperature achievable by the heat pump, circa 50°C - 55°C depending on the load side flow rate.

In the interim period, between the installation of the ground array and the return to site, the client had decided to build a new plant room, adjacent to the existing boiler room. This construction activity was still underway whilst the remaining installation activity took place. The latter consisted of:

- Mounting and connecting the main plant room ground loop manifolds
- Connection of plant room manifolds to the three sets of incoming 90mm pipework.
- Thermal transfer fluid (TTF) injection and mixing
- Installing the 3-phase electrical power supply to the plant room.
- Emplacing the heat pump
- Emplacing the ground and load side circulating pump / motor sets
- Local fabrication of a 530 litre steel, load side, buffer tank and support frame.
- All plant room plumbing - mainly in 2" steel pipework.
- All plant room electrical connections.
- Installation of controls.

The first activity on site was to fill the three separate header circuits with water and to carry out pressure testing of the full ground loop array. This was achieved using reducing mechanical couplers on the 90mm headers, connected to the mains water supply. The three pairs of 90mm headers were then connected to the main flow and return 110mm plant room manifolds using on-site butt fusion. Full flow 90mm butterfly valves installed on the manifolds provide circuit isolation for commissioning purposes.

With the complete ground loop pipework in place, it was possible to undertake the injection of the thermal transfer fluid. Because of the combination of the number of boreholes, and the use of 32mm SDR-11, 100m U-tubes, a low viscosity ethylene glycol based TTF was selected in order to minimise the parasitic pumping power associated with the ground loop circulation pump. This antifreeze solution was sourced in India and delivered to site in 200 litre barrels. The total required TTF volume was divided into 27 portions, with each portion manually injected into each borehole. Whilst injecting into any one borehole, all other boreholes were isolated. This allowed the injected fluid to displace the fresh water in the other side of the U-tube, thus eliminating any wastage or disposal of mixed antifreeze solution. Using the ground loop circulation pump, in the absence of a large-scale flush/purge cart, it was possible to open individual boreholes, and get them thoroughly mixed one at a time.

4. HEAT PUMP AND PLANT ROOM

The heat pump is an American Water Furnace Envision NKW130 reverse cycle water-to-water unit (Figure 7). This is a twin compressor heat pump using R410A, with the two individual refrigeration circuits feeding a common pair of evaporator and condenser refrigerant-to-water plate heat exchangers. The two Copeland scroll compressors are mounted one above the other, with the unit having overall physical dimensions of 607mm by 1330mm by 1803mm high. Without any water, the heat pump weighs approximately one tonne, which can present something of a handling challenge on a remote site! It has a quoted heat output of 109.7kW at B0/W50. The cooling output is quoted as 120.2kW at B30/W10. These outputs will be higher at higher ground loop temperatures in heating mode, and lower ground loop temperatures in cooling mode. The unit is supplied with a Johnson FX10 microprocessor based controller and digital display, that provides menu driven control, parameter specification, and diagnostic information. The electrical supply requirement is ~400VAC, 3-phase, 50Hz.

Figure 7: Water Furnace Envision heat pump in plant room.

For the purposes of this demonstration project, the load side of the heat pump is currently connected directly, via the load side pump motor set, to the buffer tank. The plant room layout has been kept relatively simple. There are valves and strainers on the inputs to the heat pump, and valves on the outputs of the heat pump. These provide for heat pump (flow) isolation, and protection from any debris circulated from the ground loop or buffer tank. Each of the circulating pump sets has isolation valves on their inlets and outlets. The only other "feature" is a bypass circuit that allows the ground loop circulation pump to bypass the heat pump and circulate the ground loop directly. This is useful for flushing and purging operations and for the final mixing of the TTF through the entire ground loop system. Manual air vents have been installed at high points in the plant room pipework, to allow for final air purging.

Control of the heat pump has been provided through the use of two individual digital aquastats that monitor the load-side return water temperature to the heat pump. One is used for heating control, and one for cooling control. Switching between heating and cooling is achieved with a manual switch that operates the reversing valve and selects the appropriate aquastat. The Johnson controller provides for internal safety protection of the heat pump and for cycling of the compressors as required. The only other external protection devices are flow switches mounted on the ground loop and load side pipework, which ensure there are adequate hydraulic flows to the heat pump.

5. COMMISSIONING

Once all of the ground loop and plant room pipework had been completed and leak tested, it was possible to proceed with commissioning of the GSHP. All of the shipping restraints and hold down bolts were removed from the heat pump. The ground loop was circulated whilst by-passing the heat pump, and all air vented from the system. The ground loop and load side were then circulated through the heat pump. Following this, the load and ground side strainers were inspected, cleaned and reinstalled prior to heat pump operation. Checks were made on the phase connection to ensure the correct pump and compressor rotations. In these circumstances it was helpful that both the heat pump and the pump motor controllers were provided with phase reversal protection. Given that the local electrical power supplies can be of varying quality, it is also useful that the heat pump is supplied with a phase failure protection module that checks for under and over voltage, frequency drift, and phase reversal. This protects the heat pump compressors from operating under adverse electrical conditions.

Once it was clear that the heat pump and the aquastat controls were functioning correctly, it was possible to carry out a series of simple commissioning tests. Using the Johnson controller, it was possible to observe the entering and leaving temperatures on both the load side and ground side, with one or two compressors operating. From these temperature differences it was possible to confirm that the desired flow rates were being achieved.

To demonstrate the energy delivery of the heat pump, an accurate digital thermometer was placed in the load side buffer tank. The heat pump was then run in heating mode until the buffer tank achieved maximum temperature, and the elapsed heat pump run time was recorded. From this it was possible to infer the average heating output capacity of the heat pump. This was shown to be in excess of the 100kW called for in the specification. Given the stated performance of the Water Furnace unit under the observed entering water temperatures, this was to be expected.

Although it was not a performance requirement, it was also demonstrated that the heat pump performed satisfactorily in cooling mode, by cooling the buffer tank down to room temperature.

Two observations are made here. The 530 litre volume of the buffer tank only allows for somewhere in the region of 12 to 15 minutes for a load test to be carried out at circa 100kW output, before the maximum temperature of the heat pump is achieved. It is anticipated that a more significant load will be provided in the near future, to allow for longer periods of full power heat pump operation. During the commissioning period, it was observed on all occasions that the ground side entering water temperature (EWT) was consistently around 18°C. This is significantly higher than was reported from the thermal response test. There are two explanations, i) the TRT was carried out in difficult winter conditions with snow on the ground. It is possible that the water in the test U-tube had not equilibrated with the surrounding rock temperature. ii) During commissioning, the trenches were still open and it is possible that the water temperature was affected by sunny site conditions during the day. Nonetheless, there was considerable circulation of the entire borehole field, which should have removed this effect. In the event that the ground equilibrium temperature is significantly higher than the 8.9°C reported from the TRT, this will be highly beneficial to the heating operation of the GSHP.

6. ECONOMIC AND CARBON CONSEQUENCES

GSHPs have the potential to deliver running cost savings, and/or lifetime cost savings, and/or carbon savings. However, this can only be determined once the prevailing local conditions have been assessed. In particular, the cost and carbon content of competing fuels has to be known, together with the cost and carbon content of the local electricity supply. For the evaluation of lifetime costs it is necessary to understand the local costs of drilling, labour, equipment and material supply for the entire GSHP installation. This will not be attempted here, because of the need to establish the eventual costs that might be realised in a location such as Manali, with an established GSHP capability in the region. However, it is easier to provide some indicative figures relating to primary energy consumption, fuel costs and carbon reduction.

6.1 Primary energy

A modern, well-maintained, non-condensing oil boiler will typically convert primary fuel (heating oil) at an efficiency of ~80%. This does not include the energy required to deliver the fuel to a location such as Manali. Thus each kWh of useful heat will consume 1.25 kWh of primary fuel. Most of the electricity generated in India is derived from coal-fired power stations. If we assume a conversion efficiency of 35%, 1kW of electricity will require 2.85kW of primary fuel. At an average Coefficient of Performance (COP) of 3, the GSHP will convert the 1kW of electricity to 3kW of useful heat. Thus each kW of useful heat will consume 0.95kW of primary fuel, a reduction of ~24% in primary fuel consumption. Variations can be played on this, with differing boiler, power station and heat pump efficiencies, but it is not untypical to see GSHPs delivering between 30% and 40% reductions in primary fuel efficiency.

6.2 Fuel costs

At SASE, it is reported (2014) that the cost of heating oil delivered to the site is approximately 90Rp/litre and electricity costs ~6Rp/$kWh_{e..}$ A litre of fuel oil will deliver approximately 8.6 kWh of useful heat at a boiler efficiency of 80% (Carbon Trust 2008). Thus a kWh of useful heat at SASE costs ~10.5 Rp. By comparison, if the GSHP achieves an average COP of say 3, then a kWh of electricity should deliver 3kWh of useful heat, at a cost of ~2Rp per kWh. This is a very substantial reduction in the cost of delivered heat, which would appear to make a GSHP an interesting proposition depending on the overall capital cost differential.

6.3 Carbon emissions

The UK Carbon Trust (Carbon Trust 2008) gives CO_2 emission figures of 0.3 $kgCO_2/kWh$ for coal, and 0.25 $kgCO_2/kWh$ for fuel oil. Thus an 80% efficient oil boiler will emit 0.31 $kgCO_2/kWh$ of useful heat. A coal fired powered station at 35% efficiency will be emitting 0.86 $kgCO_2/kWh$ of useful electricity generated. At a COP of 3, the GSHP will then deliver a kWh of useful heat whilst emitting 0.28 $kgCO_2/kWh$. This is only about a 10% reduction in carbon emission and is not unexpected for a system where electricity is generated from coal. For an electricity grid where other less carbon intensive generation is present, viz renewables and/or nuclear, the grid carbon content is significantly lower, and the carbon reduction potential of GSHPs is significantly higher. India already has nuclear and renewables content on its electricity grid, which reduces the overall grid carbon content. GSHPs can also achieve average COPs higher than 3. If these figures are used, the carbon reduction potential of GSHPs increases significantly.

To take the extreme case, on a local basis the SASE GSHP is in fact supplied by locally generated hydroelectricity. In this case, the carbon reduction, compared to oil fired heating will be ~100%. As India, along with the rest of the world, comes under increasing pressure to deliver carbon reductions, attention will turn to reducing the carbon content of its electricity generation, and the resulting carbon emissions of any electrically driven heat pumps will consequently reduce with time.

7. CONCLUSIONS

With significant energy challenges looming in India, the DRDO has taken the first step to investigate the potential that ground source ("geothermal") heat pump systems might offer in the delivery of heating and/or cooling to buildings. Every aspect of this project was new to the client, including the specification and procurement procedure, the thermal response testing, the equipment and materials procurement and the site installation. It was also undertaken at a remote location that posed additional challenges.

Whilst it will take some time for the performance of this 100kW closed loop GSHP installation to be fully evaluated, it has already demonstrated that it is perfectly feasible to achieve this kind and scale of installation in India. In addition, the exercise has shown that Indian manufacturers and suppliers can deliver a significant proportion of the material required for these systems. One of the benefits of GSHP systems observed elsewhere is that a significant proportion of the cost of these systems can be spent in the local economy, particularly the drilling and the site labour costs. On this project, the drilling was provided by a local contractor, the site labour, plumbing and plant room construction was sourced locally. All other equipment and materials, apart from the heat pump were sourced from Indian manufacturers or suppliers.

For the SASE project the next phase will be to link the heat pump to a useful heating load, and possibly make use of the cooling output either in the cold laboratories on the site, or for cooling one or more site buildings in the summer. The illustration of the running cost savings and the possible carbon reductions that GSHP technology can offer need to be evaluated for a variety of different Indian climatic, geological and fuel price scenarios to discover the extent to which GSHPs can make a contribution towards solving India's growing energy and carbon reduction challenges.

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