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Optimisation of a Novel Dry Air-Ground Source (DAGS) Heat Pump System

Yebiyo, M., Badran B.E., Stignor C. H., Axell, M., Gustafsson O

RISE Research Institutes of Sweden, Drottning Kristinas väg 61, Stockholm

Abstract

Ground temperatures will often fluctuate in response to heat absorption or rejection. It is important to recognize that the ground is not an infinite energy source and that it is appropriate to prevent excessive heat extraction or rejection of the ground. Significant changes in ground temperature are likely to occur if exorbitant heat extraction rates from or rejection to the ground are tolerated for long periods. These variations in the ground temperature can have major adverse effects on the coefficient of performance (COP) of a ground source heat pump (GSHP) system and, thus, the system's overall performance. However, one method of regulating ground temperature imbalance is to reject heat when the ground and ambient temperatures favor this through a dry air cooler (DAC). In order to protect the system, rather than to improve performance, DACs are often fitted to GSHP systems to reject heat in extreme conditions. An empirical transient system simulation model (TRNSYS) was developed in this study and used to analyze the control algorithms to determine the optimal operation and control strategies for the GSHP system's performance. Specifically, the paper explores the impact of using a GSHP device with a DAC. This involves examining (i) the input of energy into the GSHP system, (ii) the annual ground temperature variation and (iii) the COP. The results show that considerable savings can be achieved with optimum operation and control strategies for a GSHP system.

Keywords: Ground Source Heat Pump, ground temperature variation, control optimisiation, TRNSYS

1.0 Introduction.

GSHP systems can provide an efficient and economical alternative to gas, electric, or oil methods for heating and cooling buildings. The GSHP industry has matured from a technology standpoint yet continues to be dynamic with rapid growth rates. Péan et al. (2019) presented a concise review of the past, present, and future research highlighting some of the achievements and advantages of the GSHP system. Sarbu and Sebarchievici (2014) provided a detailed review of the GSHP systems, including their operation, energy, economic and environmental performances and recent advances.

In order to absorb or reject heat from the surrounding soil, GSHP systems have heat exchangers buried in the ground (ground loop). The rate at which heat is absorbed from the ground must not allow the temperature of the ground to fall too low during the winter, and during the summer, the heat absorbed in the winter must somehow be replenished. Otherwise, this will result in soil thermal imbalance (the mismatch between heat extraction and ground rejection) that can degrade the efficiency of the GSHP device.

Researchers are looking at hybrid GSHP systems to help solve the soil thermal imbalance problem. A hybrid GSHP system uses several different geothermal sources, outdoor air and geothermal sources, to balance the annual thermal load.

Three buildings (two cooling-dominated and one heating-dominated) using hybrid GSHP systems for a year were tracked and analysed by Hackel and Pertzborn (2011). In TRNSYS tool, models of hybrid GSHP systems were constructed; a closed-circuit cooling tower (CCCT, also referred to as a fluid cooler) was used as an additional device to meet a portion of the peak heating or cooling load. Their work has demonstrated that cost-effective and environmentally friendly hybrid GSHP systems are available.

Alavy et al. (2013) developed a rigorous mathematical and computational approach for sizing hybrid GSHP systems. They tested their methodology on ten cases, from residential to commercial and industrial buildings, and concluded that the method could result in significant reductions in initial costs of installation, payback period, and operation costs when compared to non-hybrid GSHP systems.

Lee et al. (2014) conducted an experimental study to compare the transient performance characteristics between a GSHP and a hybrid GSHP, accounting for the degradation of the ground thermal condition during long-term operation. They found that the hybrid GSHP lessened the deterioration of the ground thermal condition and increased the system performance during long-term operation. For the hybrid GSHP, supplementary heat rejecters or extractors were incorporated into the GSHP to control some portion of the heat rejection or extraction rate of the ground heat exchanger (GHE) to reduce the cooling or heating load imposed on the GHE.

Lee et al. (2015) proposed a hybrid GSHP system to solve the performance degradation of the GSHP systems under imbalanced load conditions. They designed a hybrid GSHP system composed of three flow loops: a refrigerant flow loop, a ground flow loop, and a supplemental flow loop. In their study, the transient performance characteristics of the hybrid GSHP were measured and analysed in the cooling mode at various flow loop configurations, including the hybrid GSHP systems with serial and parallel configurations. Their research showed that during the hybrid operation, the hybrid GSHP system with serial configuration showed a relatively higher coefficient of performance (COP) than the hybrid GSHP with parallel configuration due to the lower heat accumulation in the ground under the degraded ground thermal condition. In addition, they concluded that under the steady state condition, the COPs in the hybrid GSHP systems with serial and parallel configurations were 15% and 7% higher, respectively, than that in the standard GSHP system.

Beckers, Aguirre and Tester (2018) studied various hybrid and non-hybrid GSHP and air source heat pump (ASHP) configurations using TRNSYS, calibrated with data measured at the cellular tower shelter in Varna, New York, United States (Varna Site). To limit the impact of thermal imbalance, the hybrid GSHP with an air economiser (free cooling) directly blows cold ambient air into the shelter, and the hybrid GSHP with a dry fluid cooler uses cold ambient air to cool down the borehole heat exchanger heat transfer fluid. Their simulations indicated that hybrid GSHP systems allow the owner to save up to 30 per cent of lifetime electricity consumption compared to hybrid ASHP systems for cooling cellular tower shelters for the weather and operating conditions of the Varna Site. They found that a hybrid GSHP system with an air economiser works better if the aim is to minimise energy consumption and CO2 emissions. Omitting an air economiser, the next best alternative is a hybrid GSHP with a dry fluid cooler, followed by a GSHP-only scheme. They also found that increasing the total depth of the borehole heat exchanger would further minimise energy consumption while increasing the total cost of ownership marginally.

Liu et al. (2019) proposed a hybrid GSHP system with an auxiliary cooling tower to relieve soil thermal accumulation and performance degradation over a long-time operation in the cooling-dominated area in Shanghai. To study the proposed system's performance and feasibility, the hybrid GSHP system simulation model was constructed in TRNSYS, and measurement data validated the reliability of the simulation. They concluded that the hybrid GSHP system remained stable in terms of the temperature variation of the soil, and the outlet temperature of the buried pipes were lower compared to standard GSHP systems over a ten-year operation.

Hou and Taherian (2019) designed and assembled a hybrid GSHP system in TRNSYS to examine the overall effectiveness of various pipe lengths. In their design, the hybrid GSHP was presented as a horizontal ground loop in parallel with a liquid dry cooler. They run simulations for a full calendar year to generate important analytical data such as annual energy consumption and heat rate. After analysing the results of various pipe lengths and diverter setpoint temperatures, the optimal values were recommended by them.

Hou et al. (2020) simulated and tested the effectiveness of a newly-developed temperature-controlled diverter for a hybrid GSHP system which combined a horizontal ground loop and a liquid dry cooler. Their main target was to examine the double-set temperature diverter's overall effectiveness by switching the control strategies. Both short-term and long-term simulations were carried out in TRNSYS to analyse energy variation and soil thermal condition with respect to different diverter heating and cooling set temperatures. The short-term simulation results showed that the system's overall performance was mainly influenced by the diverter's heating set temperatures rather than cooling. Also, the usage ratio of the liquid dry cooler was decreasing while the diverter's heating set temperature was increasing. Combining long-term COP values and soil thermal variation, they recommended that diverter heating set temperatures ranging from 8 °C to 10 °C could provide the system with a favourable COP value and less soil temperature impact in climate zones. They also found that the loss in soil temperature over ten years of operation was shown to be lessened by employing the liquid dry cooler enhanced with the dual setpoint diverter.

In order to protect the system, rather than to boost performance, DACs are often fitted to GSHP systems to reject heat in extreme conditions. Opportunities exist to use a DAC to improve the GSHP 's performance. These control systems are not, however, documented in any literature. This paper presents the development of a new TRNSYS model to investigate the effects of using DAC by selectively rejecting heat through DAC to reduce the degree of ground temperature saturation and thermal imbalance. The overview of the GSHP system and its operation, the setup of the simulation, the GSHP system and the various components used to create an empirical model of GSHP TRNSYS are further presented in this paper.

This paper explicitly explores the impact of using a DAC in combination with a GSHP device. This involves investigating (i) the rejection of heat, (ii) the input of energy to the GSHP system, fan and circulation pumps, (iii) COP and (iv) the variation in ground temperature. Additionally, the TRNSYS model was used to examine a number of control algorithms to identify optimal operation and control strategies for the GSHP system to improve system efficiency.

2.0 Description of the New System and Its Operation.

The proposed system uses the London South Bank University (LSBU) GSHP installation at one of the buildings called (K2) but operates differently from the initial setup. Four HP Reversible EKW130 units (WaterFurnace, Inc) are used by LSBU's K2 building GSHP device. Each has a nominal heating capacity of 120 kW and a cooling capacity of 125 kW. Via a closed device, heat is transported to and from the ground using 159 vertical energy piles that are embedded in the structure's base and drilled into the London clay. The system's source side consists of energy piles and header pipes to which the HPs supply or extract heat through a pumped heat transfer fluide, exchanging energy between the building and the ground. The GSHP system provides the building's heat and cooling output entirely.

The original system used a DAC designed to work when the heat sink temperature was too high or too low. Therefore, the DAC was used to prevent the heat pump from working outside its protected envelope as a safety system. The DAC was tactically used in the proposed system to increase the efficiency and performance of the heat pump and, thus, the system. Figure 1 below illustrates the simulated system. This shows that to accomplish the best COP, the system is managed to provide heat rejection via the DAC rather than the ground loop. This is based on a theory that the Carnot COP of a heat pump is substantially affected with a 1 K decrease of temperature difference , resulting in a 3 % increase in COP. Therefore, when it provides more favorable heat sink temperatures (and thus a higher COP) compared to those produced by the field, the DAC can be used selectively. The proposed system has the potential to save energy but should not require additional components compared to the existing system, although it is controlled differently. The performance improvement of the proposed system is discussed in the following sections.

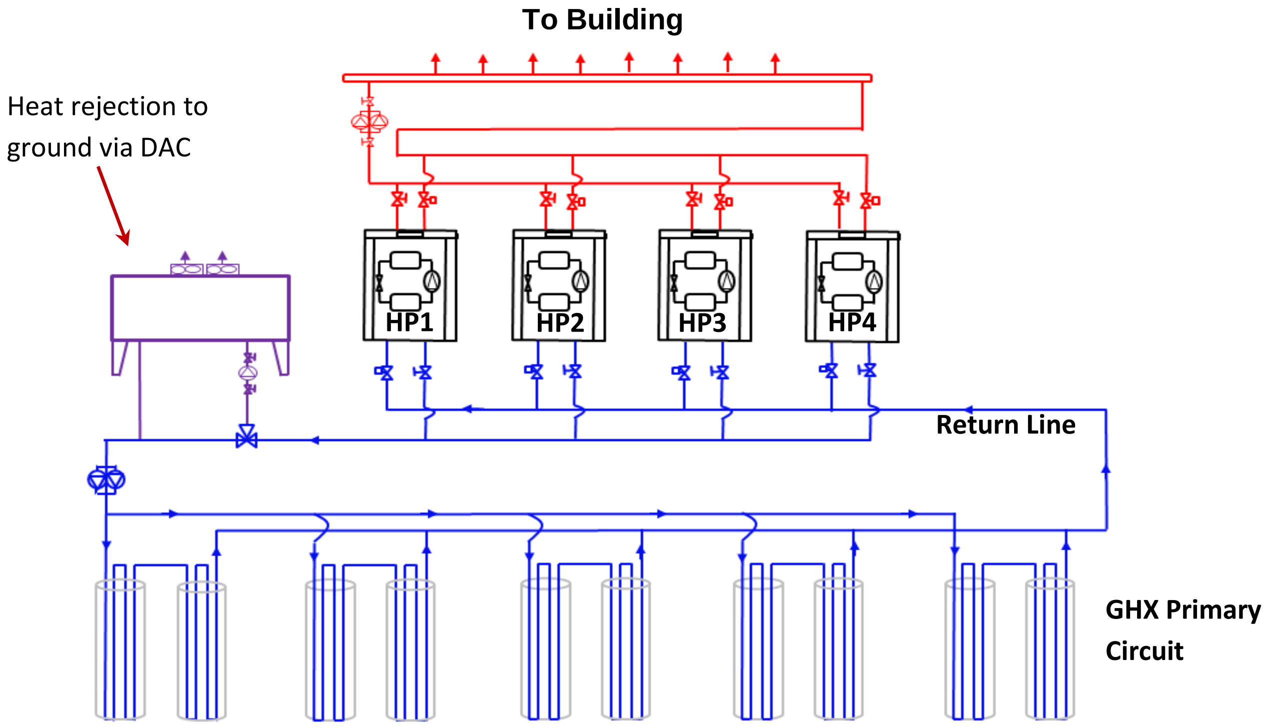

Figure 1: *Schematic of the System Simulated.*

3.0 The Simulation Setup.

In order to simulate the experimental observations, a model was built with the simulation software TRNSYS 17 , (2010). This allows the construction of a GSHP system simulator that closely resembles and simulates the actual HP installation. The main components of the GSHP system that were used to build the simulation model are the ground heat exchanger (Type 557a), the HP model (Type 668), the circulating pumps (Type 682) as flow stream loads, DAC (Type 511), tempering valve (Type 11), and tee piece (Type 511). The following sections describe how the various system components work, which are replicated by interconnecting a set of models.

3.1 Ground Heat Exchanger (Type 557a).

The ground heat exchanger component (Type 557a) was set up with the appropriate geometrical configuration and relevant ground thermal properties, some of which were derived from the thermal response testing carried out in the GSHP design stage. Type 557a models a set of equal vertical U-tube heat exchangers which thermally interact with the ground. This ground heat exchanger model is most used in GSHP applications. Depending on the temperature of the heat carrier fluid and the ground, a heat carrier fluid is pumped through the ground heat exchanger and either rejects heat or absorbs heat from the ground. In the current work, 159 energy piles are used to exploit the ground's heating and cooling capacity.

3.2 Heat Pump Model (Type 688).

The HP model (Type 668) relies upon catalogue data readily available from HP manufacturers for the performance measurement related to the HP that is being simulated. At the heart of the component are two data files: a file containing cooling performance data and a file containing heating performance data. Both data files provide capacity and power draw of the HP (whether in heating or cooling mode) as functions of entering source fluid temperature and entering load fluid temperature; these establish the performance envelope of the HP over a range of ground source side temperatures and a range of load side temperatures.

The Type 668 HP is equipped with two control signals, one for heating and cooling. If the heating and cooling control signals are both ON, the model will ignore the cooling control signal and will operate in heating mode. However, the heating mode takes precedence over the cooling mode. The data used to build this HP model were obtained from the manufacturer WaterFurnace.

The HP's COP in heating is given by equation 1.

$$\mathrm{COP}_{hp} = \frac{\mathrm{Q_{HP}}\ [\mathrm{kW}]}{\mathrm{W_{HP}}\ [\mathrm{kW}]} \quad (1)$$

The amount of energy absorbed from the source fluid stream in heating is given by equation 2.

$$Q_{absorbed} = Cap_{heating} - P_{heating} \quad (2)$$

The outlet temperatures of the two liquid streams can then be calculated using equations 3 and 4.

$$T_{Source,out} = T_{source,in} - \frac{Q_{absorbed}}{m_{source}Cp_{source}} \quad (3)$$

$$T_{load,out} = T_{load,in} - \frac{Cap_{heating}}{m_{load}Cp_{load}} \quad (4)$$

The HP's COP in cooling mode is given by equation 5.

$$\mathrm{COP}_{R} = \frac{\mathrm{Q_{HP}}\ [\mathrm{kW}]}{\mathrm{W_{HP}}\ [\mathrm{kW}]} \quad (5)$$

The amount of energy rejected by the source fluid stream in cooling mode is given by equation 6

$$Q_{absorbed} = Cap_{cooling} + P_{cooling} \quad (6)$$

The outlet temperatures of the two liquid streams can then be calculated using equations 7 and 8.

$$T_{Source,out} = T_{source,in} + \frac{Q_{rejected}}{m_{source}Cp_{source}} \quad (7)$$

$$T_{load,out} = T_{load,in} + \frac{Cap_{cooling}}{m_{load}Cp_{load}} \quad (8)$$

3.3 Circulation Pumps (Type 741).

There are two pumps for circulation. The Type 741 pump model may produce any mass flow rate between zero and its rated flow rate; in reality, each pump represents a group of pumps. Similar to the majority of pumps and fans in TRNSYS, Type 741 accepts the mass flow rate as input but only uses it to check the mass balance. Based on its rated flow rate parameter and the current value of its control signal input, Type 741 determines the downstream flow rate. The pressure rise, overall pump efficiency, motor efficiency, and fluid properties are used to compute the pump's power draw.

3.4 DAC (Type 511).

A dry air cooler, represented by Type 511, cools a liquid stream by blowing air across the coils holding the liquid. This model assumes that the device can be modelled as a single-pass, cross-flow heat exchanger.

3.5 Tempering valve (Type 11b).

Thermal systems frequently require the use of pipe or duct "tee-pieces," mixers, and diverters that are controlled externally. This valve enables the system to be managed according to the fluid's temperature, leaving the heat pump.

3.6 Tee piece (Type 511h).

The empirical GSHP system model used to examine various control techniques is schematically depicted in Figure 2. In this application of the Type 511h model, modes 1 and 6 are used to model how a tee-piece would work to thoroughly mix two intake streams of the same fluid at various temperatures and/or relative humidity. Table 1 provides a list of the assumptions used to simulate the TRNSYS system model.

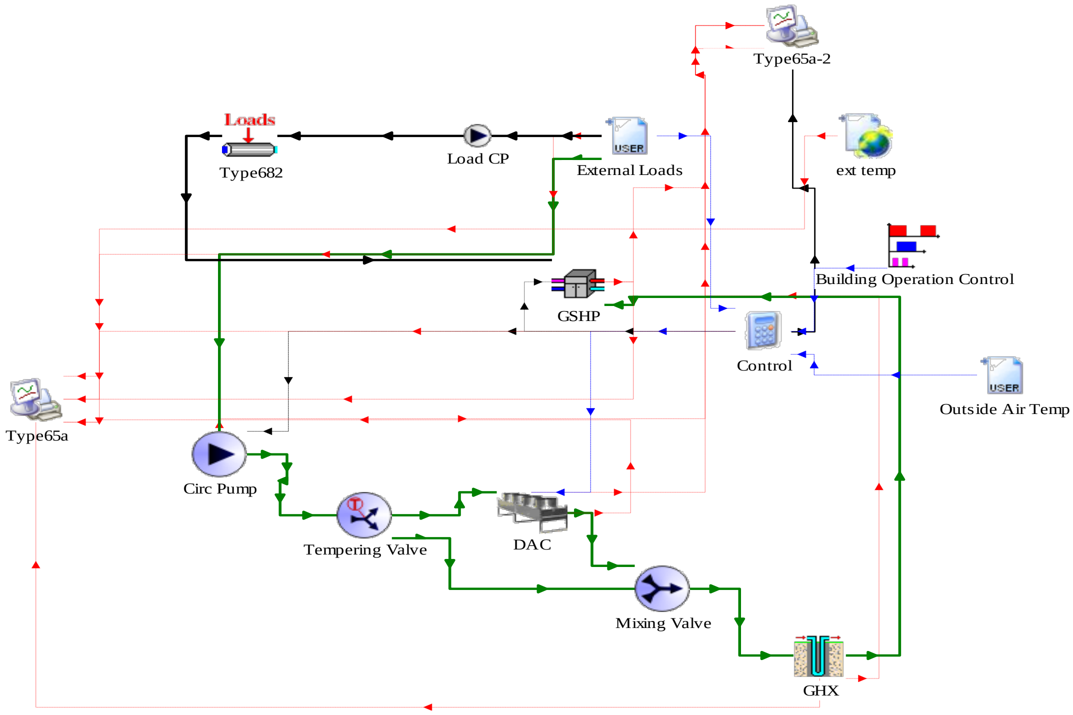

Figure 2: *Schematics of the DAC simulation setup connected to the GSHP system.*

Table 1: *List of model inputs and assumptions*

Occupancy period 13 hours every day except weekends
Historical outside air temperature (OAT)
Flow and return fluid temperatures on both the source and load side of the system
Heating and cooling performance data of the heat pump model
Heat pump and circulation pumps to operate in heating mode if the OAT > 18°C
Heat pump and circulation pumps to operate in heating mode if the OAT < 14°C

4.0 Model Validation.

The empirical TRNSYS model created was validated using experimental data from the real GSHP system installation at LSBU. The many physical elements of the system have been kept as close to reality as feasible, and numerous experiments have been carried out to validate the model. A comparison of the independently calculated COP values with those anticipated by the model shows a reasonable level of agreement. The maximum variance shown in Figure 3 is approximately 7%.

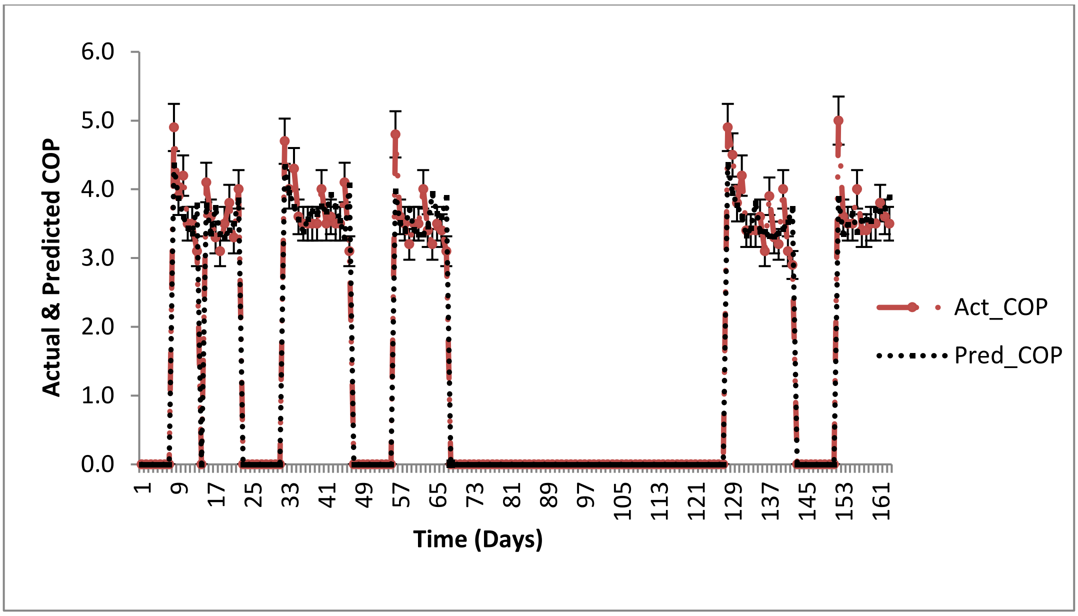

Figure 3: *Comparison of actual and predicted COP.*

5.0 Development of Novel Control Strategies Using DAC.

The development of novel control strategies using a DAC is given in this section. When the fluid temperature leaving the HP is higher than a specific threshold, as shown in Table 2, the control methods investigated in this work enable the DAC to activate the various control strategies known as scenarios CS1, CS2, CS3, CS4 and CS5. These conditions have been put to the test and measured against the system's typical operating state in order to explore the impact of operating the DAC at various temperature setpoints. Examining the annual change in ground temperature, the energy input into the GSHP system, and the output coefficient are all necessary for this (COP). The outcomes of the simulated scenarios are thoroughly explained in Sections 5.1 to 5.4.

Controls that have been properly installed and configured are essential for upholding the necessary performance and safety standards while utilizing minimal energy. It is possible to regulate the GSHP system's performance by utilizing a DAC to selectively reject heat to the air. The estimated seasonal or daily ground temperature and the anticipated/available energy demand of the building can be used to manage this. Building energy use and carbon emissions could be reduced if the control system is well-designed, implemented, and uses design temperatures that maximize the system's coefficient of performance (COP).

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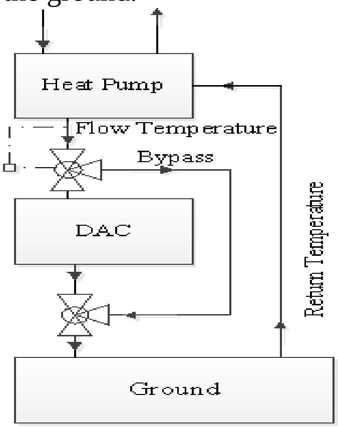
Table 2: *Different control strategy approaches using DAC***Control Strategy 1 (CS1)**
The DAC is controlled based on the fluid flow temperature exiting the HP. When the DAC is on, then the fluid is cooled down using the DAC; otherwise, the fluid bypasses the DAC and enters the ground.



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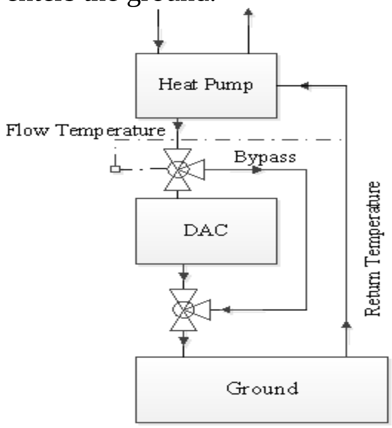
Control Strategy 2 (CS2)
The DAC is controlled based on fluid return temperature leaving the ground. When the DAC is on, then the fluid is cooled down using the DAC; otherwise, the fluid bypasses the DAC and enters the ground.



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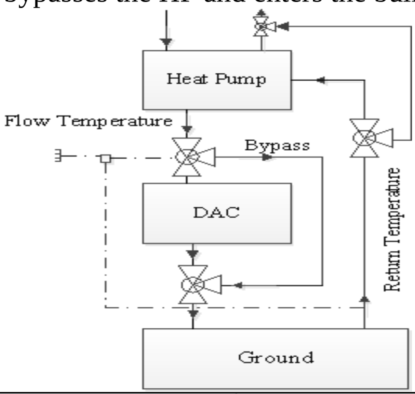
Control Strategy 3 (CS3)
This is a free cooling option; the DAC is controlled based on the difference between fluid return temperature, leaving the ground and outside air temperature. When the DAC is on, then the fluid is cooled down using the DAC; otherwise, the fluid bypasses the DAC and enters the ground. The fluid returning from the ground bypasses the HP and enters the building.



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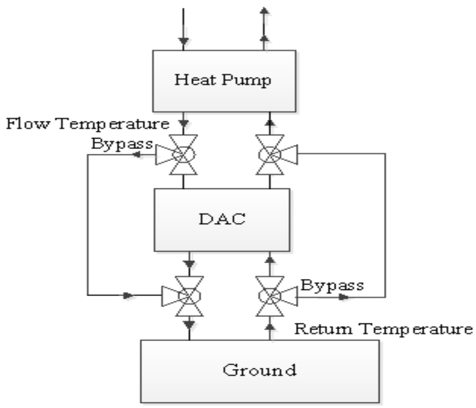
Control Strategy 4 (CS4)
In this control strategy, there is an option of cooling the fluid either on fluid flow temperature exiting the heat pump or on fluid return temperature leaving the ground; otherwise, the fluid bypasses the DAC and enters the ground or the HP.



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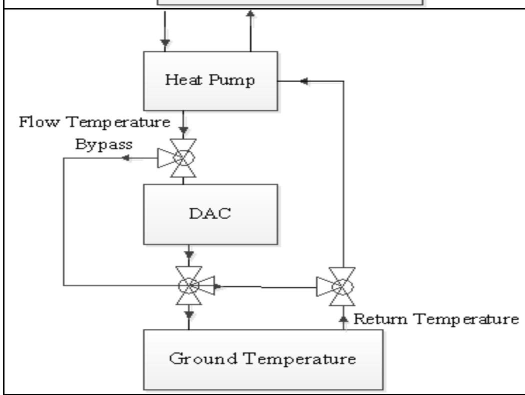

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Control Strategy 5 (CS5)
The DAC is controlled based on the ground temperature and ambient air temperature, when the ground temperature reaches a certain value then the DAC can either be used to reject heat to the ground or the fluid bypasses the ground and enters the heat pump.
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In order to reduce ground saturation, which has an impact on the system's performance, the existing system model was modified to reject heat into the ground. The opportunity was therefore seized to explore the effects of various control strategy approaches employing the DAC on HP performance and ground temperature change after developing and establishing a verified empirical TRNSYS system model. The DAC circuit, circulation pumps, and the HP should all be turned on or off at different times according to the control methodologies used in this study. The three categories of HP power, each circulating pump's power, and DAC fan power add up to the total amount of electrical power used by the system. Figure 4 below displays a flow diagram of the examined control techniques.

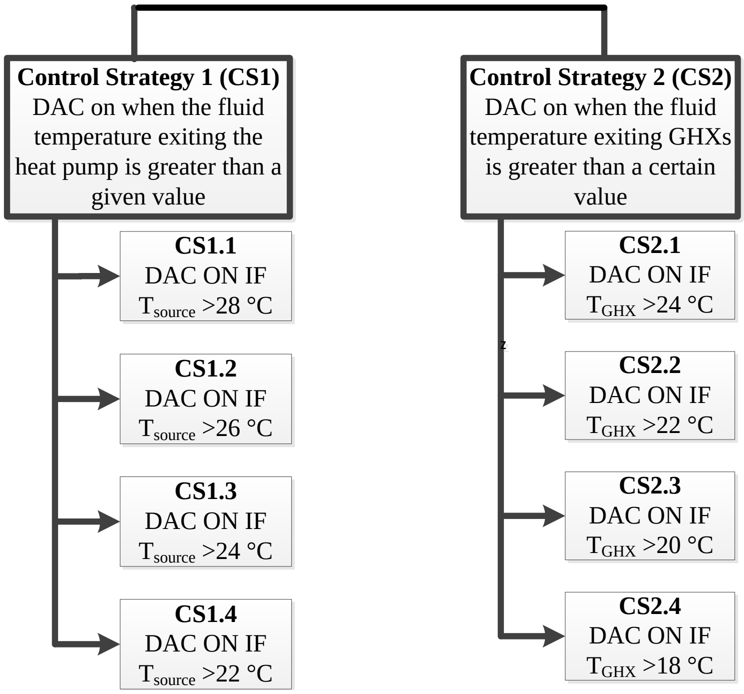

Figure 4: *Flow diagram of the control strategies.*

5.1Effect of DAC on COP.

Figure 5 shows the cooling COP value of the GSHP system at various temperature set points. It should be noted that the COP values for all four of the specified temperature scenarios were quite similar at the start of the season in April to June 2013. Time Period A is the period during which the DAC is not active. In Time Period B, there is a difference in COP between the options, and the DAC is either working fully or partially during the months of June and October 2013. The DAC was used to lower the leaving fluid temperature from the HP by rejecting the heat back to the ground at a lower temperature than the normal operating leaving fluid temperature of the HP, which is the only reason for the difference in COP. The GSHPs COP value decreases continuously with increasing setpoint temperature. For the first year of GSHP system operation, the COP values for cooling are highest for the lowest setpoint temperature.

Setting the temperature setpoint control to 22 ° C results in a cooling COP of 6.2, which is 19.2% higher than the average operating scenario. As a result, the cooling COP value is reduced to 5.2 in comparison to the regular operating scenario. An energy and exergy analysis of a GSHP system in Ontario (Canada) by Kizilkan and Dincer (2015) revealed that the system's efficiency in the heating mode was marginally increased when the fluid temperature entering the HP was greater.

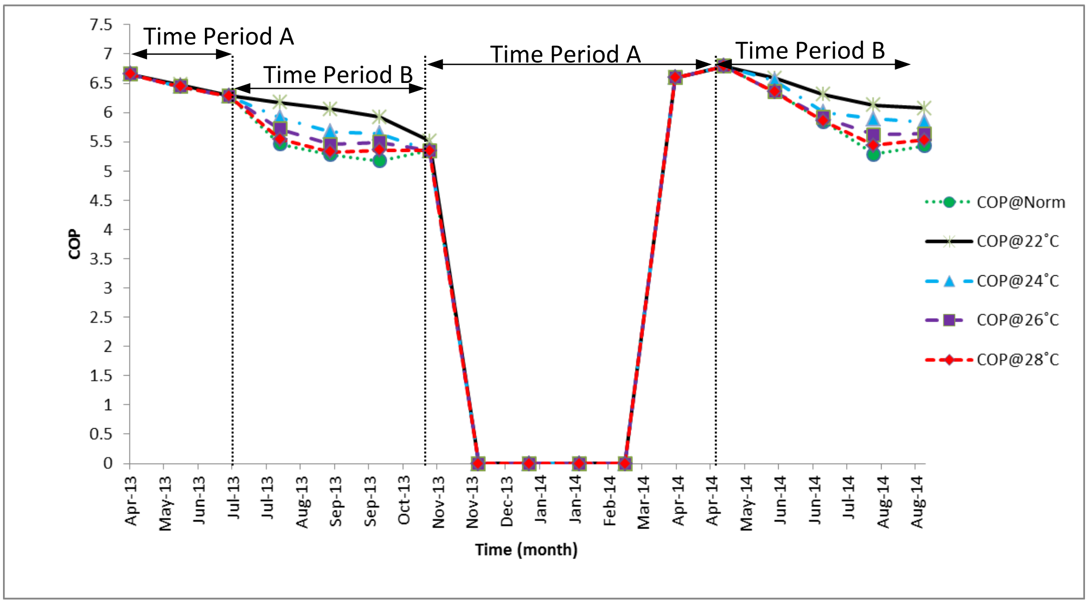

Figure 5: *Average Monthly system COP.*

5.2 Effect of DAC on Ground Temperature

Along with looking into how the DAC's operating cycle affects the device's efficiency, a look into how it affects ground temperature is also conducted. The simulation results for ground temperature over the course of a year are shown in Figure 6. The results demonstrate that when the setpoint temperature varies, the four separate setpoint operation temperatures of the DAC cause variations in the ground temperature.

In Time Period A, when the DAC is not operating at the beginning of the cooling season, the ground temperature is similar, and hence changing the ground temperature setpoints does not affect it at all. Therefore, the ground temperature for all scenarios remains constant. However, in Time Period B, the temperature variation between the scenarios becomes clear that the more the DAC is running, the lower the ground temperature variation is. After one year of cooling mode operation, the maximum ground temperature is 23°C for the normal operation duration, compared to 20°C for the lowest set point temperature, which is 15 per cent lower than the normal operation.

This impacted on COP, and therefore by reducing the ground temperature from 23 to 20 °C, the overall system performance has improved by approximately 9 %, and this can be seen clearly in Figure 5 above. If excessive heat extraction rates from or rejection to the ground are tolerated for prolonged periods, then significant changes in ground temperature are likely to occur; such changes in ground temperature may have a significant detrimental effect on the overall COP system, as well as a significant impact on the atmosphere. By using simpler heat rejection or 'free cooling' techniques, Zoi and Constantinos (2012) suggested three control strategies to mitigate this major change in ground temperature. The first one determines the set point at which a cooling tower starts its operation according to the fluid temperature exiting HP, and ambient air wet-bulb temperature exceeds a given set point. The second one activates the cooling tower when the fluid temperature exiting GHX is higher than a specific value. The third one sets the cooling tower on when the fluid temperature exiting HP is higher than a given value.

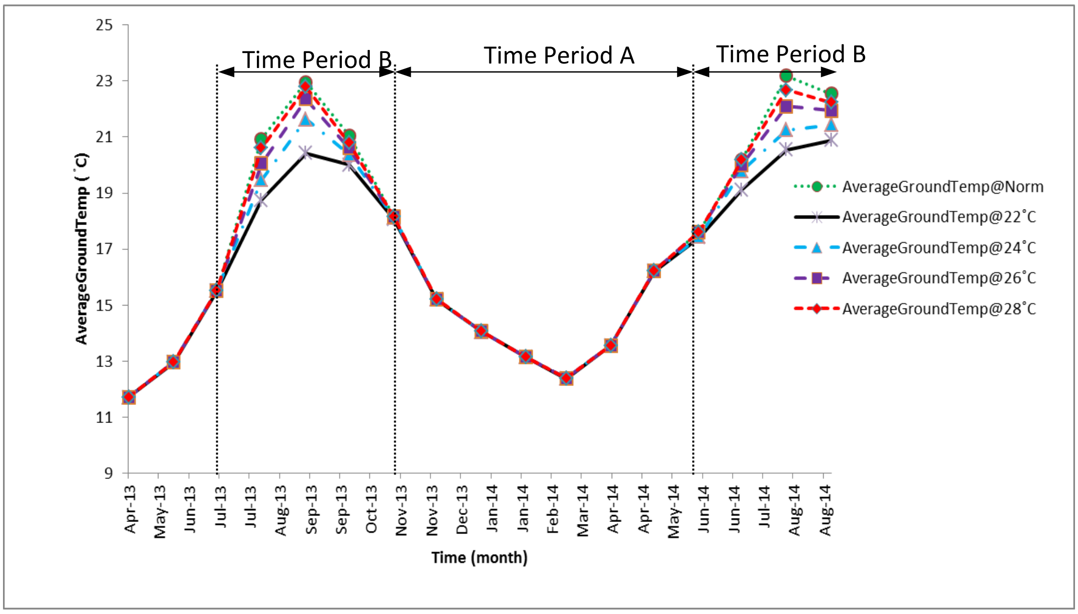

Figure 6: *Monthly ground temperature variations.*

With the decrease of average ground temperature around the ground heat exchanger, the temperature difference between the ground and the circulated heat carrier fluid decreases; this phenomenon has both advantages and disadvantages for the system. While this gradual shift in temperature increases the COP value during the cooling season, it also decreases the system's COP value during the heating season.

5.3 Effect of DAC on Heat Pump Energy Consumption.

The total monthly HP energy consumption for scenarios CS1, CS2, CS3 and CS4 are presented in Figure 7. The operation cycle of the DAC can determine whether the GSHP system consumes more energy compared to a GSHP system without DAC. Figure 7 shows that the maximum energy consumption of the HP was 7923 kWh and 7669 kWh, respectively, between the periods of April 2013 and August 2014, both of which occurred while the system was operating without DAC support. Also, when the DAC was controlled at the highest set point temperature of 28 °C, these dynamics can be shown clearly in Figure 6 during Time Period B. Time Period A demonstrates that the performance of the four set points remains unchanged when the DAC is off. Time Period B shows that this zone also illustrates the advantages of decreasing the ground temperature while the DAC was running at various set points, as shown in Figure 6 of the system's energy input. Reducing the temperature of the ground helps to decrease the temperature differential between the temperature leaving the ground loop heat exchanger and the temperature leaving HP, thus increasing the system's COP.

Comparisons of the four scenarios in Time Period B between the periods of July and September 2013 showed that the system's energy consumption decreased by 8% when the lowest control setpoint of 22 ° C (CS4) was compared to the system's usual operating conditions. Likewise, the system's lowest energy consumption was 267 kWh during the transition period to the heating mode. Zhao et al. (2003) proposed a theoretical and experimental study to investigate the impact of several capacity control techniques on the HP's energy efficiency, i.e. turning the compressor on / off, regulating on / off times of intake and discharge valves, concentration ratios of the refrigerant mixture, and speed of the compressor.

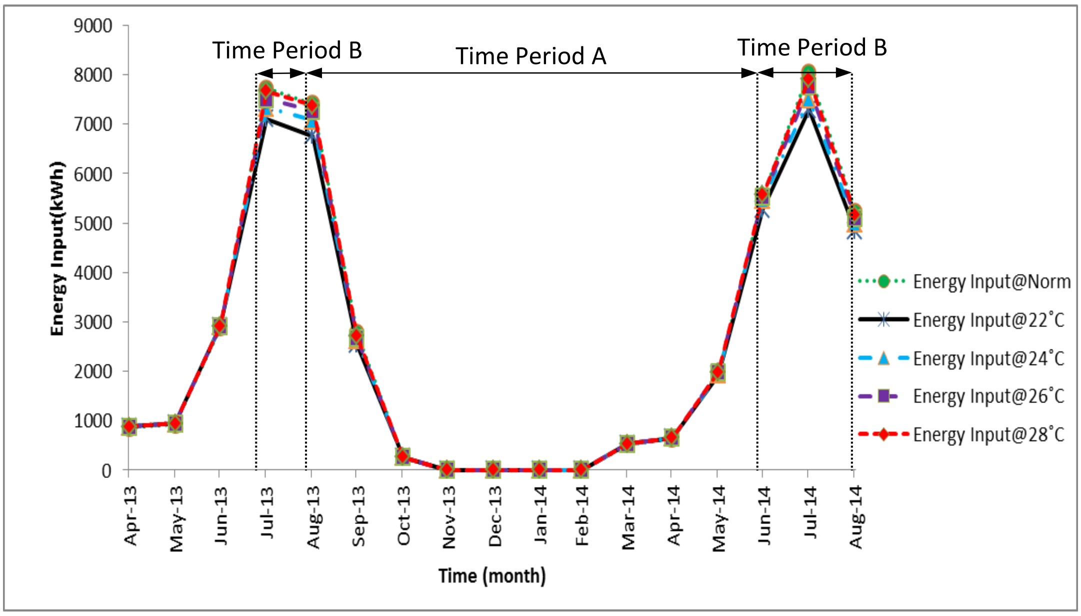

Figure 7: *Monthly HP energy consumption.*

5.4 Proportion of Energy Utilisation

The total proportion of energy consumption of the HP, circulation pump and the fan are shown in Figure 8 below. It indicates that the compressor accounts for 72 per cent of the total system's annual electricity consumption, followed by the circulation pumps, which use 20 per cent of the system's total energy supply. The DAC's 9 per cent energy consumption is comparatively small compared to the energy input of the compressor.

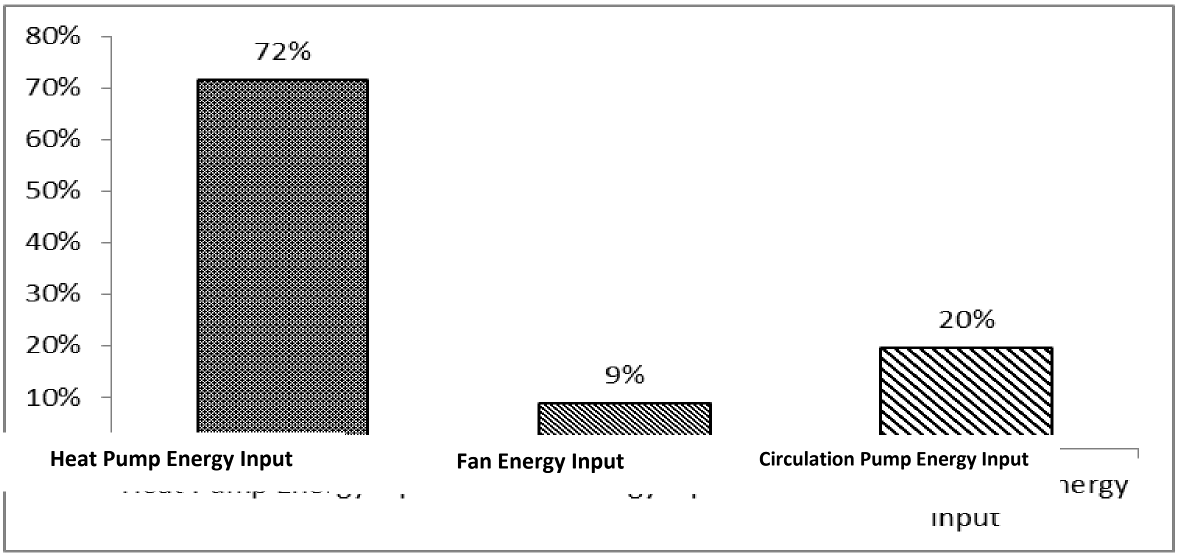

Figure 8: Proportion of energy utilisation of HP, circulation pump and fan CS1.

5.5 Economics of The Control Strategy

The financial and CO_2 emission savings for each temperature set point were compared with the regular operation of the system in this section. The additional monthly CO_2 emission savings ($kgCO_2$) that can be achieved by enforcing the various temperature control setpoints are shown in figure 8. The graph indicates that a cumulative CO_2 emission saving of 420 $kgCO_2$ was achieved in July 2014. This is also the point where the highest COP and highest ground temperature have been reported in connection with Figures 5 and 6. This occurred, notably, at the lowest set temperature point of 22 ° C. In addition, the lowest CO_2 emission savings were approximately 20 $kgCO_2$, and this occurred at the

28 ° C maximum temperature set stage. As shown, the lowest temperature set point can produce a saving of approximately 17 per cent relative to the highest temperature set point. The lowest temperature set point will often achieve cost savings of approximately 18 per cent relative to the maximum temperature set point.

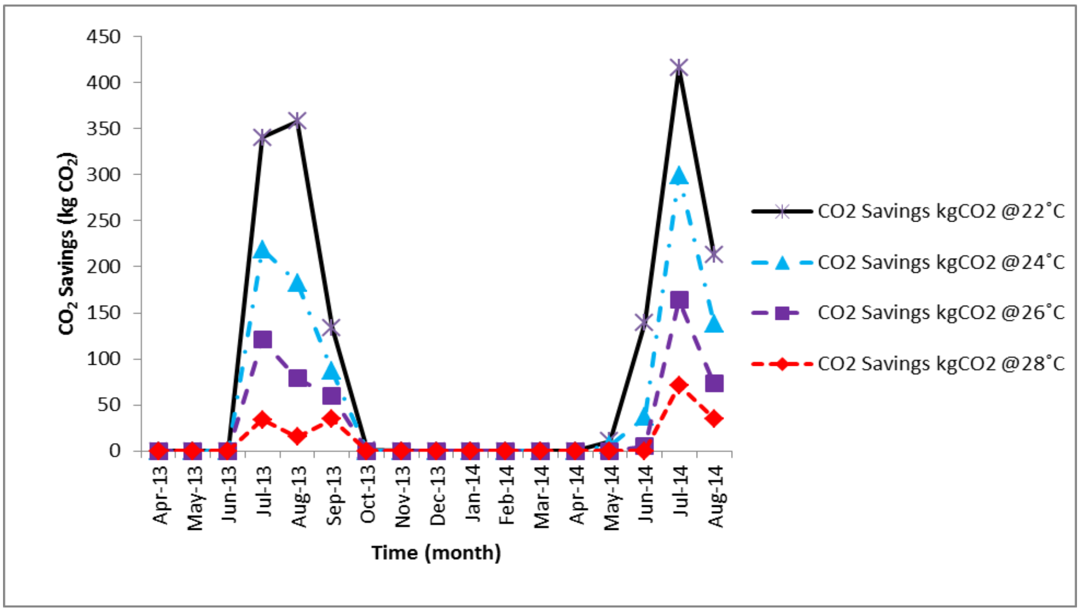

Figure 8: *Monthly CO2 emission savings from the different control strategies.*

Specifically, Figure 9 shows the possible additional cost savings that can be made relative to the standard system operation from the various temperature set points. Figure 9 also shows that using the lowest temperature set point of 22 ° C, a maximum cost saving of £ 110 was achieved in July 2014. In addition, for the same month, the most economical cost savings were around £ 20, and this happened at the maximum fixed temperature point of 28 ° C. Compared to the maximum temperature set point, the lowest temperature set point will achieve cost savings of approximately 18 per cent.

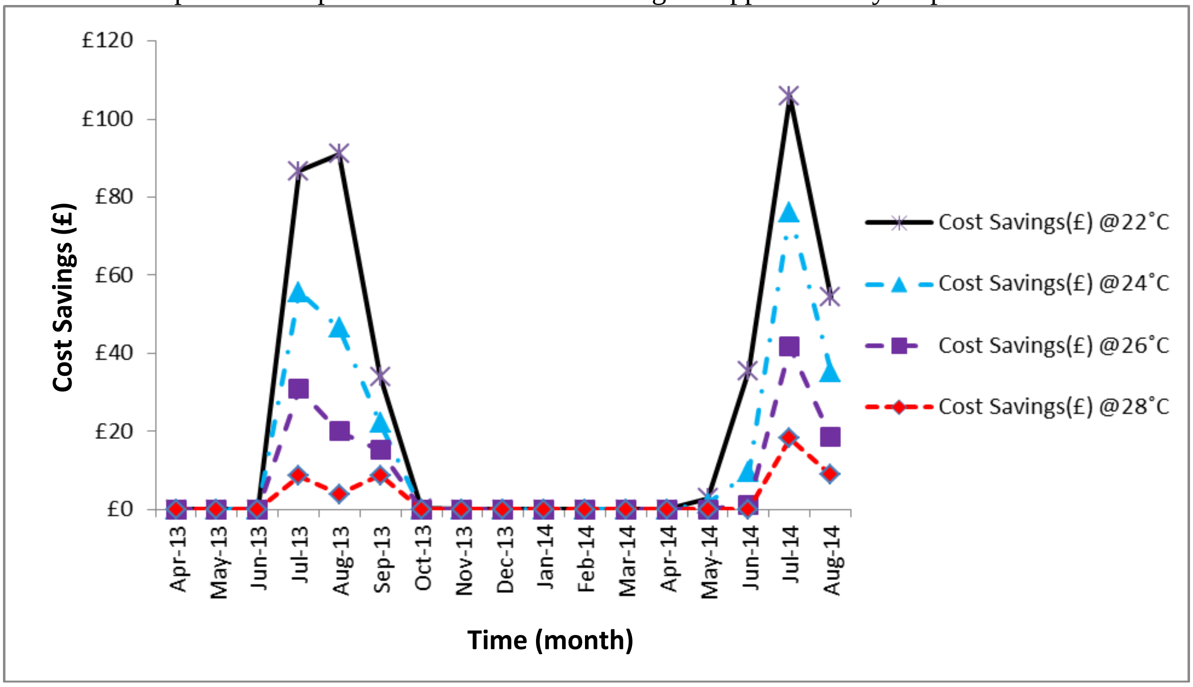

Figure 9 *Monthly cost savings from different control strategies CS1*

6.0 Conclusion

During the net cooling cycle for a university building, this paper identified various control strategies for GSHP device optimisation. The investigation centred on the effect of DAC on ground heat rejection, system COP, variance in ground temperature, minimisation of compressor and circulation pump electrical power consumption, assuming certain building load values, and maximum cooling capacity of HP and DAC.

This paper has shown that a substantial reduction in GSHP running costs, electrical power usage, and an increase in the system's COP could be achieved by using and regulating a DAC using different temperature setpoints. However, it is difficult to argue that this is the most economically profitable example, not only because the heating cycle is not tested, but also because unit selection has not considered the investment and maintenance costs. This is the subject of further work.

This paper has established that the best of those tested to control the activity of DAC in the GSHPs is the lowest temperature setpoint control. A comparison of these four scenarios shows that substantial cost and carbon reductions can be accomplished and that all current control methods achieve improved management of system operations, leading to an additional reduction in energy usage, carbon and cost savings. It is possible to use these remarks as guidelines for potential GSHP designers.

References

Alavy, M., Nguyen, H.V., Leong, W.H., Dworkin, S.B., 2013. A methodology and computerised approach for optimising hybrid ground source heat pump system design. Renewable Energy, 57: 404–412.

Beckers, K.F., Aguirre, G.A., Tester, JW, 2018. Hybrid ground-source heat pump systems for cooling-dominated applications: Experimental and numerical case-study of cooling for cellular tower shelters. Energy and Buildings, 177: 341-350.

Hackel, S., Pertzborn, A., 2011. Effective design and operation of hybrid ground-source heat pumps three case studies. Energy and Buildings, 43(12): 3497–3504.

Hou, G., Taherian, H., 2019. Performance analysis of a hybrid ground source heat pump system integrated with liquid dry cooler. Applied Thermal Engineering, 159: 113830.

Hou, G., Taherian, H., Li, L., Fuse, J., Moradi, J., 2020. System performance analysis of a hybrid ground source heat pump with optimal control strategies based on numerical simulations. Geothermics, 86: 101849.

Kizilkan O, Dincer I. (2015). Borehole thermal energy storage system for heating applications: thermodynamic performance assessment. Energy Convers Manage 2015; 90:53–61.

Lee, J.S., Park, H., Kim, Y., 2014. Transient performance characteristics of a hybrid ground-source heat pump in the cooling mode. Applied Energy, 123: 121–128.

Lee, J.S., Song, KS, Ahn, J.H., Kim, Y., 2015. Comparison on the transient cooling performances of hybrid ground-source heat pumps with various flow loop configurations. Energy, 82: 678-685.

Liu, Z., Li, Y., Xu, W., Yin, H., Gao, J., Jin, G., Lun, L., Jin, G, 2019. Performance and feasibility study of hybrid ground source heat pump system assisted with a cooling tower for one office building based on one Shanghai case. Energy, 173: 28-37.

Sarbu I., Sebarchievici C., 2014. General review of ground-source heat pump systems for heating and cooling of buildings. Energy and Buildings, 70: 441–454.

TRNSYS, (2021). Version 17. Transient system simulation program solar energy engineering laboratory Madison: University of Wisconsin. Available from: http://sel.me.wisc.edu/trnsys/features/features.html. [Accessed: 6th August 2021].

Zoi, S. and Constantinos, R. (2012). Control Strategy for minimising the electric power consumption of Hybrid Ground Source Heat Pump System. Proceeding of ECOS JUNE 26-29, 2012, PERUGIA, ITALY.