Feasibility Study for a Geothermal Heating System: A Case Study

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BACKGROUND

The Department of Science and Technology (DST) together with the Eastern Cape Department of Education (ECDOE) are co-funding the construction of a science centre in the village of Cofimvaba in the Eastern Cape. The purpose of the science centre is to promote the study of science, technology, engineering and mathematics (STEM) in the school district.

The Council for Science and Industrial Research (CSIR) was appointed as DST's Implementing Agent for the project. The express purpose of this appointment was to pilot, evaluate and demonstrate the application and efficacy of innovative building technologies (IBTs) on the project in accordance with a South African Government Cabinet Resolution of August 2013 regarding the application of IBTs in government projects.

A key objective is to apply IBTs to enhance the economic, social, environmental and institutional sustainability of public buildings. For this project attention is focused on achieving net-zero energy and water consumption, and reducing waste water disposal and construction waste. A key strategy to achieve a net-zero building was to eliminate reliance on mechanical heating and cooling.

CONTEXT

In an effort to balance the energy supply and demand of the proposed new science centre in Cofimvaba a number of strategies are being pursued, including passive heating and cooling. Among the technologies investigated in this regard is the use of Geothermal Heating and Cooling (GHC).

Cofimvaba is situated in the Intsika Yethu Local Municipality approximately 77 kilometres south-east of Queenstown in the Eastern Cape Province. The site measures 1,7ha in extent and is located on the corner of Hill and Main Streets. Most portions of the site is covered by grass and small to large sized boulders. The site has a moderate fall of approximately 10m towards the south-east.

As noted in the geotechnical investigation rep0ort (Plichta and Mulovhedzi 2016) the site is located in a valley and is underlain by red and grey mudstone and sandstone of Burgersdorp Formation, Beaufort Group, Lower Triassic Age. The younger dolerite of Jurassic age overlies the mudstone and sandstone along the slopes of the valley. Mudstone is a fine grained sedimentary rock composed of clay or mud and silt-sized particles, whereas sandstone is composed of sand-sized grains cemented together in a matrix of silt or clay sized particles and is also a sedimentary rock (Plichta *et al* 2016). The report notes that the completely weathered (residual) mudstone has high clay content with a heaving characteristic which forms numerous surface cracks in the soil upon drying. The report notes that the soils on the site are not suitable for platform/terrace construction, as they have high clay content or are contaminated by building rubble or fill. The report therefore recommends that the soil for the area of construction being 40m x 40m be excavated to a depth of 1,5m and removed to spoil. The removal of this material presented the opportunity to investigate the efficacy of the installation of a closed loop GHC system to attenuate indoor air temperature.

The term “geothermal energy” is used, generally, to describe the high-temperature energy that is derived from the heat flux from the earth’s deep interior and that one finds either in very deep boreholes or in certain specific locations in the earth’s crust, or both. However, GHC is not primarily concerned with geothermal energy but is more focused on the relatively new science of “thermogeology” which involves the study of ground source heat, i.e. the low quality form of heat (or thermal energy) that is stored in the ground at normal temperatures (Lutchman 2018).

There are several different types of GHC systems which are categorized by the geothermal heat exchangers layouts that are employed. Heat exchanger layouts are divided into two categories: open loops and closed loops. For purposes of this study only the horizontal closed loop system was considered for the reason described above. Furthermore, for purposes of the analysis a ground temperature of 19°C was assumed.

METHODOLOGY

The methodology for the feasibility study followed was as follows:

- Fan coil units (FCUs) are designed to work in conjunction with the geothermal heat exchangers.
- High level concept designs of two different cases were performed to determine the order of equipment required in the facility.
- Conclusions and recommendations were drawn on the analysis and the effectiveness of each of the cases.

The cases that were analysed were:

- Case 1 where geothermal tempering is used, i.e. water heated in a geothermal heat exchanger supplies heating to fan coil units to temper the air in occupancy areas.
- Case 2 where geothermal heating is used, i.e. water heated in a ground source heat pump system supplies heating to fan coil units to increase the air temperature in the occupancy areas to achieve thermal comfort.

ANALYSIS

The analysis involved the following:

- Heat load analysis
- Fan coil unit analysis
- Geothermal heat exchanger analysis

For purposes of this paper the fan coil unit analysis is omitted as the unit was selected based on the performance characteristics of fan coil units available from a commercial FCU manufacturer.

Heat Load Analysis

The climate chart for Cofimvaba indicates that heating the facility rather than cooling the facility is required. A heating load analysis was carried out to determine the worst-case heating requirement of the facility. The climate chart for Cofimvaba indicates that June and July are the coldest months reaching a mean daily temperature of 3 °C (Figure 1). This temperature is therefore used in the heating load analysis. Furthermore the analysis was performed for 08:00 in the morning the assumption being that this was the time that occupants would enter the building.

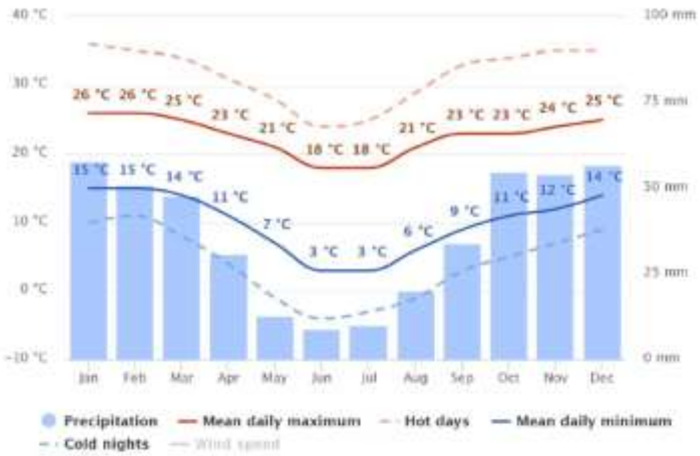

Figure 1: Cofimvaba climate chart (Meteonorm 2018)

The heat load analysis was determined by calculating the energy required to increase the required ventilation air to the required comfort temperature considering the heat gains from the occupants, the solar irradiation and the heat loss of the building.

The following assumptions were made for purposes of the calculation:

- Maximum daily solar direct normal irradiance (DNI) was found to be 600 W/m², thus it was taken to be 300 W/m² at 08:00. A cosine loss of 83 percent was incorporated due to the low sun angle at 08:00 and the orientation of the building, resulting in an overall solar irradiance of 51 W/m². The solar irradiance was added as a heat gain only to occupancy areas.
- A U-value of 1 W/m².K was assumed for the building.
- The required comfort temperature was assumed to be 22 °C.
- The heat gain from the occupants was assumed to be 130 W/person (78 W sensible and 52 W latent).
- The room height of 3 m was used for each of the occupancy areas.
- The density of the air was assumed to be 1.13 kg/m³.
- The analysis was done for the building in a steady state condition with full occupancy.
- The number of air changes per hour was determined by the requirements of SANS 10400-O.

The heat load analysis was determined by calculating the energy required to increase the required ventilation air to the required comfort temperature considering the heat gains from the occupants, the solar irradiance and the heat loss of the building. The heat load analysis is summarised in the equation below (Lutchman 2018):

$$\dot{Q}_{req} = \dot{Q}_A + \dot{Q}_B - \dot{Q}_O - \dot{Q}_S \quad [1]$$

where Q_{req} is the total heating power required, Q_A is the power required to increase the temperature of the ambient air from the external conditions to the required internal conditions, Q_B is the building heat loss, Q_O is the heat gain due to occupancy activity, and Q_S is the heat gain due to solar irradiation.

The total heat load of the building taking heat gain (irradiance and occupant) and heat loss into account was calculated using equation 1 to be 85.9 kW. This value was used as the basis for the feasibility study.

Geothermal Heat Exchanger Analysis

An analysis of the geothermal heat exchanger system was then performed to determine the length of piping required in the ground loop to meet the heating requirements of the building. The layout is shown in Figure 2.

Figure 2: Layout of spiral earth coil (Lutchman 2018)

An area requirement of the piping is more useful than a length requirement since an area requirement could easily be compared with what is available on the site. Horizontal ground loops are typically laid out in a “spiral” from as shown in Figure 2. The geometry of the spiral is shown in Figure 3.

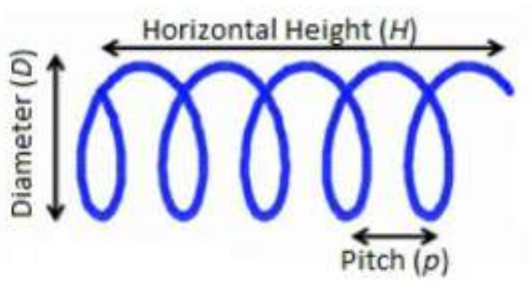

Figure 3: Geometry of a spiral (Lutchman 2018)

For purposes of calculating the length of piping required the following assumptions were made:

- The diameter of each coil is 1 m.
- The pitch between coil loops is 0.5 m
- The distance between adjacent coils is 0.5 m
- The thermal resistance of the HDPE piping was determined to be 0.0472 m·K/W
- The thermal resistance of the soil was determined to be 0.605 m·K/W
- The heat transfer rate per unit length of the piping was determined to be 5.67 W/m

The total length of a spiral can be calculated as follows (Lutchman 2018):

$$\begin{aligned} L &= \frac{\dot{Q}_{req}}{q} \\ &= \frac{85.9 \times 10^3}{5.67} \\ &= 15150\,\text{m} \\ &= 15.1\,\text{km} \end{aligned} \quad [2]$$

Based on equation 2 the total length of piping required to achieve the required heat transfer rate of 85.9KW was 15.1 km. Laying this in the spiral pattern as illustrated in Figure 2 would require an area of 70 m x 70 m. However, the area of excavations was only 40 m x 40 m. The calculations were therefore rerun based on the diminished area. This indicated that a hypothetical heat capacity of 28860W would be realised which would provide a final air temperature in the occupancy areas of 16.7 °C, which is insufficient to meet the design requirements of 22 °C.

Heat Exchanger with Heat Pump Analysis

As noted in Case 1 in the methodology, i.e. water heated in a geothermal heat exchanger supplies heating to fan coil units to temper the air in occupancy areas as shown in Figure 3 below.

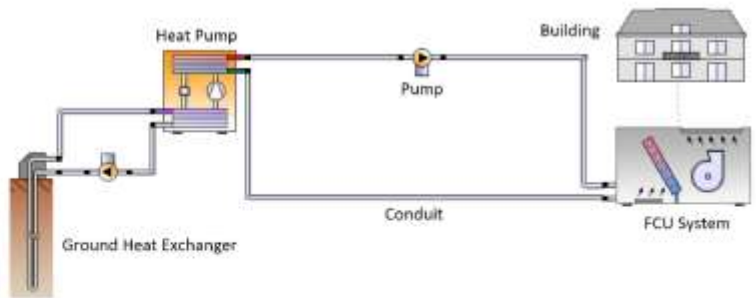

Figure 3: Layout of geothermal heat exchanger with a heat pump system (Lutchman 2018)

The analysis indicates that given the area available the temperature of the air is 6 °C short of providing the required heating for occupancy comfort. Accordingly the use of a geothermal heat exchanger with a heat pump was then analysed to determine whether it would contribute to meeting the design requirements of 22 °C.

A heat pump extracts more thermal energy from the ground loop water such that the return temperature of the water from the heat pump to the ground loop reaches a level that provides the needed temperature difference to raise the heat transfer rate in the ground loop. If the temperature could be brought down to 7.5 °C, the ground loop will provide a per metre heat transfer of (Lutchman 2018):

$$\begin{aligned} q &= \frac{T_s - T_f}{R_t} \\ &= \frac{19 - 7.5}{0.0472 + 0.605} \\ &= 17.6\,\text{W/m} \end{aligned} \quad [3]$$

Substituting 17.6 W/m for 5.67 W/m in equations 2 and 3 for determining pipe length yields a pipe length of 4 876 m and an area of 1 533 m² which falls within the area of excavation. However, to operate the heat pump will require an input power of 17.9 kW: thus, 85.9 kW of heat can be provided but an input mechanical-electrical power of 17.9 kW is required to achieve the required temperature of 22 °C.

CONCLUSION

The analysis For Case 1 shows that in the case of geothermal tempering, while discomfort is reduced to some extent, the required temperature is not achieved. A much larger geothermal installation would be required to get closer to the target temperature which would require a substantially larger area of excavation. Given that the loop is only 1.5m below ground the performance of the loop could also potentially be negatively impacted by seasonal variation (3m is typically the preferred depth to avoid seasonal variation). Either option, i.e. larger loop area and/or deeper loop depth, would substantially increase the excavation required.

It must also be noted that this case study sought to achieve a specific temperature: a temperature range could also be used of say between 18 °C to 26 °C. However, even then the geothermal tempering is insufficient.

The analysis for Case 2 shows that with geothermal heating the required temperature could be provided but that it would require an input power which would complicate a key objective of this project, viz, net-zero energy. Nonetheless, this approach merits closer scrutiny where appropriate.

The analysis indicates that there are a number of factors which influence the performance of GHC, not least being the field area, the depth of installation and the temperature of the ground. A decision to use GHC will require substantial investigations and detailed design to determine its ultimate efficacy.

Finally it may well be, as the analysis seems to indicate, that there isn't sufficient temperature difference between the ambient air and the ground temperature in South Africa for this system to be beneficial.

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