Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Implementing a Geothermal Heat Pump in a School in Coyhaique, Chile

Nicolás Hurtado, Nicolás Pérez-Estay, Pablo Valdenegro, Diego Aravena, Diego Morata

Plaza Ercilla 803, Santiago, Chile

nicolas.hurtado@ug.uchile.cl

Keywords: Southern Chile, Geothermal heat pump, Geothermal open loop, School, Electrical resistivity methods

ABSTRACT

Coyhaique is the most populated city of the Aysén region in southern Chile. With nearly 60,000 inhabitants, it has been catalogued as one of the most polluted cities in Latin America. This environmental issue is caused by the use of firewood as a heating source. In 2017, the Andean Geothermal Center of Excellence (CEGA) along with several regional entities obtained a regional government funding for the design and installation of a heating system with a geothermal heat pump for a public school. The prototype replaced the wood burning system in ~50% of the school's infrastructure, and it is intended to serve as an example for others schools in the region, contributing to the regional plan for reducing PM emissions.

In order to characterize the aquifer and quantify the available resource, electrical resistivity tomography (ERT) and transient electro-magnetic (TEM) surveys were performed. The aquifer's electrical resistivity was interpreted to range between 70 – 250 Ωm, showing the water table at 7 m depth underneath the school. The drilling of two shallow wells (extraction and reinjection) confirmed that the aquifer could be reached at 9 m depth and correlated with a resistivity of ~200 Ωm. The extracted groundwater flow is around 5 L/s, but the pumping test showed a much higher capacity (over 20 L/s).

School's infrastructure thermal insulation was inspected before the design of the system, which is based on environmental temperature and focuses on improvements to reach national norms. The final installation consists of a 50 kW_t heating system powered by two geothermal heat pumps, covering 11 classrooms through a distributed fan-coil array. The use of fan-coils results in a higher overall efficiency than the use of radiators, since they allow the heat pump to work with lower temperatures.

1. INTRODUCTION

1.1 Air quality in Coyhaique city

Coyhaique,the capital city of the Aysén region, Chilean Patagonia, is the most populated city of the region with ~57,818 inhabitants (around 55% of the population in the region) (INE Chile, 2017). Due to its geographical location (45.6º S, 72.1º W, 310 m.a.s.l.), it presents low temperatures during the year, with an annual mean temperature of 8.2 °C, been June and July the coldest months with a minimum that reached -19.2 °C in 2002 (Hepp, Reyes, & Muñoz, 2018).

In this context, the high consumption of low quality firewood with a high moisture content (mainly in the residential and public sector with over 70% of their energy consumption) generates saturation of PM10 and PM2.5 (particles with a diameter below 10 µm and 2.5 µm respectively). This situation is aggravated due to the use of inefficient heaters and low thermal insulation in edifications, making the city's inhabitants face thermal discomfort (Ministerio de Energía, 2018). This conditions make Coyhaique the third most pullet city for PM2.5 in Latin America and Caribbean (IQAir, 2018).

1.2 Project and school

This project has been financed by a regional fund awarded to CEGA in 2017, for an amount of about USD $300,000 (CLP $200,000,000) that covers salaries, travels, construction costs, among others. The project also includes the participation of other regional institutions, such as the Regional Ministry Secretariat (Secretaría Regional Ministerial, SEREMI) of Education, Directorate for Municipal Education (Dirección de Educación Municipal, DEM), SEREMI of Energy and SEREMI of the Environment.

The school Liceo Bicentenario Altos del Mackay (founded in 2012) was selected due to: the presence of groundwater, building's thermal insulation, school community interest, solution-projected impact, among others. Through infrastructure extensions, new pavilions have been added, giving it around 1,500 m^2 of constructed surface area and an enrollment over 400 students divided into 13 courses.

One segment of the school was heated by radiators fed by two wood-fired boilers, while the rest used individual wood-burning stoves per classroom. On average, the entire school consumed about 200 m^3 of dry firewood per year, which was stored in a woodshed and involved an annual cost of USD $10,000. These systems used to be reinforced with gas, paraffin and electric heaters, as well as the inclusion of failed aerothermal equipment to cover the thermal needs.

The final intervention consists of 11 classrooms, a corridor and two bathrooms (around 600 m^2). These spaces were selected to apply the geothermal prototype, due to students' thermal discomfort and/or the use of individual firewood stoves. The entire establishment could not be intervened due to budget restrictions. The school warehouse was used as a mechanical room for the geothermal heating system (Figure 1).

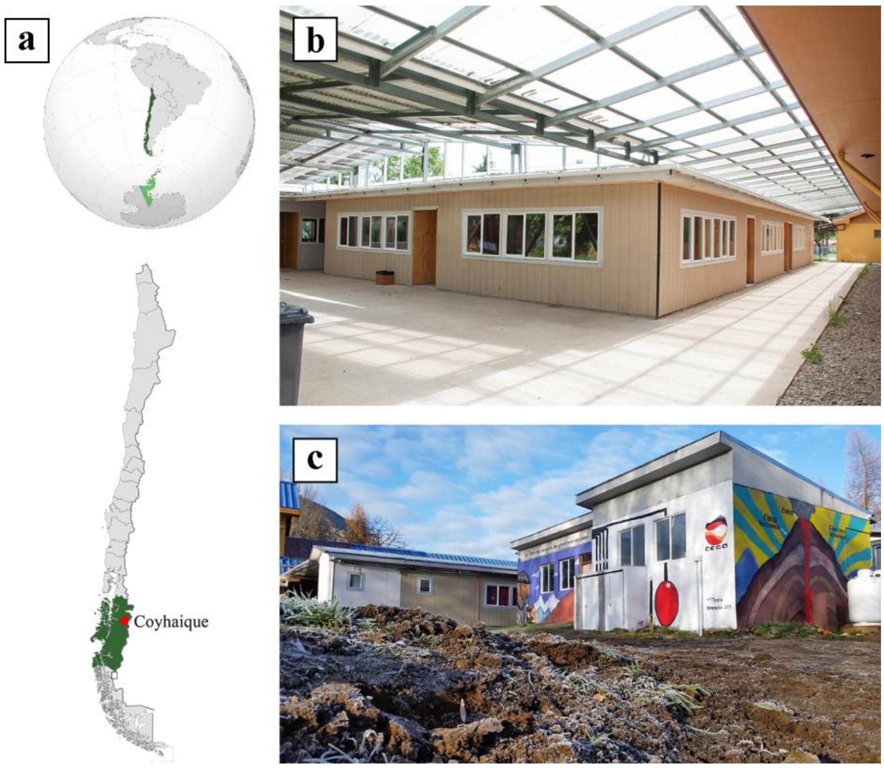

Figure 1: School Altos del Mackay. a) World-scale location (source: Wikimedia Commons[1], modified). b) One of the school's pavilions intervened. c) Mechanical room exterior.

The project includes three main areas of development: 1) quantification of the geothermal resource, 2) design and installation of the heating system and 3) analysis of social impact and technology transfer. In this work, the first two areas will be addressed. Figure 2 shows the project workflow.

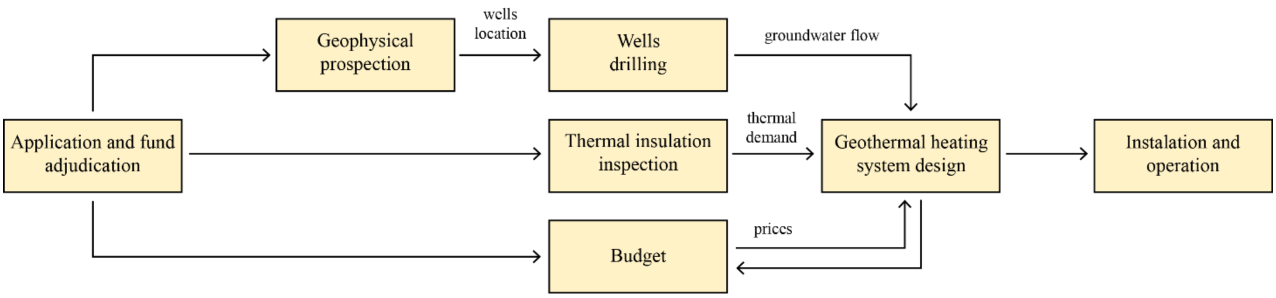

Figure 2: Project steps.

1.3 Geothermal Heat Pump

Heat pumps use mechanical work (normally powered by electricity or gas) to transfer heat from a low temperature source to a higher temperature sink. This transfer takes less work than converting primary energy into heat; in other words, it requires less power than the heating or cooling delivered. This efficiency is quantified by the coefficient of performance (COP), which is the ratio between the amount of heat delivered and the work required. Higher efficiencies can be achieved if the source and sink temperatures are close together (Rees, 2016). For heating, the heat delivered can calculated with (CANMET Energy Technology Centre, 2005):

$$\dot{Q}_d = \dot{Q}_t \frac{COP}{COP-1} \tag{1}$$

Where $\dot{Q}_d$, $\dot{Q}_t$ are heat delivered and heat transferred, respectively. Geothermal heat pump systems take advantage of the lower temperature variance of ground through the year, compared to ambient air. Temperature of ground or water sources is consequently generally closer to room temperature than the ambient air, achieving a higher efficiency. Open loop geothermal collector uses natural water from a well (groundwater) or a body of water (lakes, rivers, etc.) and takes it into a heat exchanger inside the heat pump (Figure 3).

[1] Source: https://commons.wikimedia.org/wiki/File:Mapa_loc_Ais%C3%A9n.svg

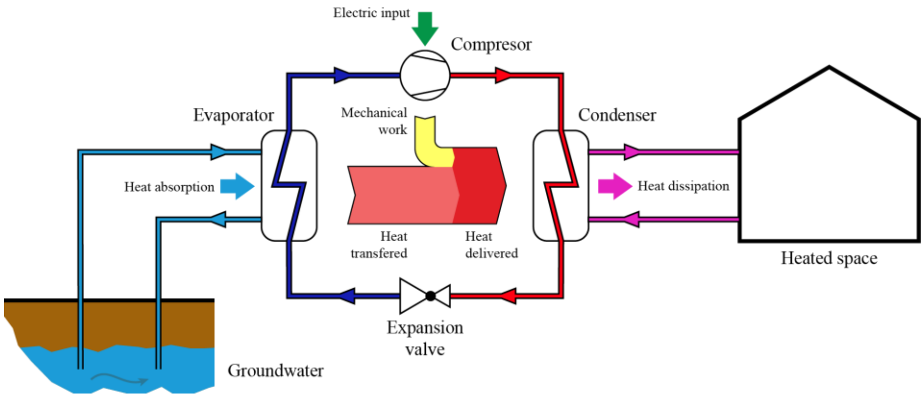

Figure 3: Groundwater open loop geothermal heat pump system used for heating purposes.

Heat transferred in the evaporator is equal to the sensible heat in the natural water flow, and it is calculated as:

$$\dot{Q}_{transferred} = \dot{m}_{H_2O} \cdot c_{p\ H_2O} \cdot \Delta T \quad (2)$$

Where $\dot{m}_{H_2O}$, $c_{p\ H_2O}$, ΔT are natural water mass flow rate, water specific heat at constant pressure and water temperature difference, respectively.

2. BASE LINE FOR HEATING SYSTEM DESIGN

Accurate design of the heating system requires: i) definition of the resource beneath the school (in this case, groundwater), and ii) heat demand of the school with the specific building features. In this section, we will discuss both base-line scenarios for the Liceo Bicentenario Altos del Mackay case. The following methodologies can be applied in others places of the Aysén Region, as well as others settings worldwide. This will convey valuable information and inputs for a successful design of the heating system.

2.1 Geophysics prospection to find groundwater

The lack of space and absence of high thermal-gradient in the Coyhaique basin constrains our project to be an open loop system. In this context, we carried out several electrical resistivity tomographies (ERT) and transient electromagnetic (TEM) surveys to define the existence of groundwater and define its depth below the school. Both methods showed the electrical resistivity distribution of the soil, obtaining an image of the subsurface. We chose these methods because electrical resistivity is one of the most helpful physical proprieties to observe groundwater (Kirsch, 2009). Details of these methodologies, as physical theory, data processing and modeling can be found in geophysical survey literature as (Telford, Geldart, & Sheriff, 1990) and others. Specifically, seven ERT profiles were performed with the *Tigre, Allied Associates* equipment, with a maximum profile length of 150 m, composed by 32 electrodes spaced by 5 m, and ~30 m of prospection depth. This was complemented with six TEM measurements carried out with *FastSnap TEM* equipment with a square-transmission-loop of 25x25 m, a square-receiver-loop of 5x5 m, and a prospection depth of ~50 – 70 m. Spatial distribution of the different surveys with respect to the school can be observed in Figure 4.

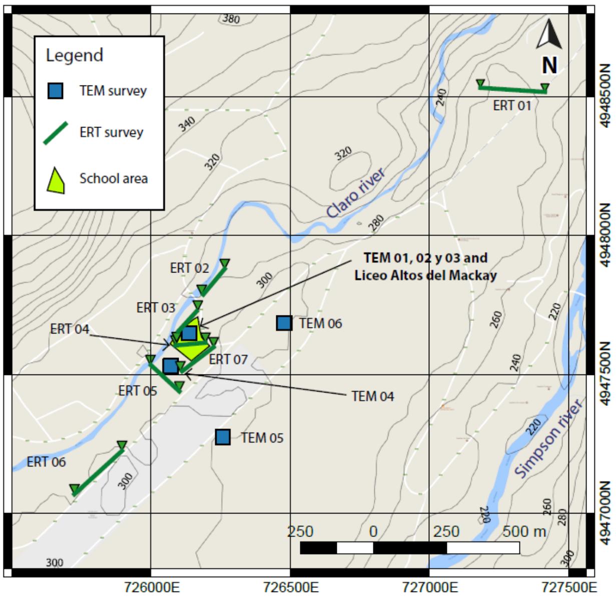

Figure 4: Geological map of the area with the location of the geophysical survey near to the Liceo Bicentenario Altos del Mackay school. White lines represent local roads, an elevation contours are also observables. WGS 84 UTM 18S coordinate system.

To determine groundwater existence and its depth, it is necessary to define an electrical resistivity value representative of the saturated soil. For this purpose, we made an ERT profile close to a river where groundwater is expected to be found (see ERT-02 in Figure 4). Specifically, this profile was located parallel to the river direction, at ~8 – 10 m of horizontal distance from the river and raised 3 m in the vertical direction (over a fluvial terrace). Results of this profile are presented in Figure 5a. This profile is an image of the electrical resistivity distribution of the subsurface along the line drawn in Figure 4. Two main domains can be observed in ERT-02 profile, with the first one at shallower depths between 270 and ~265 m.a.s.l., with resistivity ranging between 300 – 10,000 Ωm. The second one is distributed between ~265 m.a.s.l. and the bottom of the profile, with resistivity values ranging between 200 – 30 Ωm. The first unit is interpreted as dry soil, because we distinguish the inexistence of saturated soils in the first 2 – 3 m according to a soil outcrop close to the ERT-02 profile. The lower units are interpreted as the groundwater saturating fluvial soils (a common feature of river terraces), due to similarities between the river water level and the upper limits of this unit (268 m.a.s.l. and 265 m.a.s.l. respectively). Therefore, it is possible to define an electrical resistivity range from 200 – 30 Ωm where groundwater is expected. This range of values is observable in every ERT between the bottom of the profile and different depths, suggesting this unit is continuous along the fluvial domain of the Claro River.

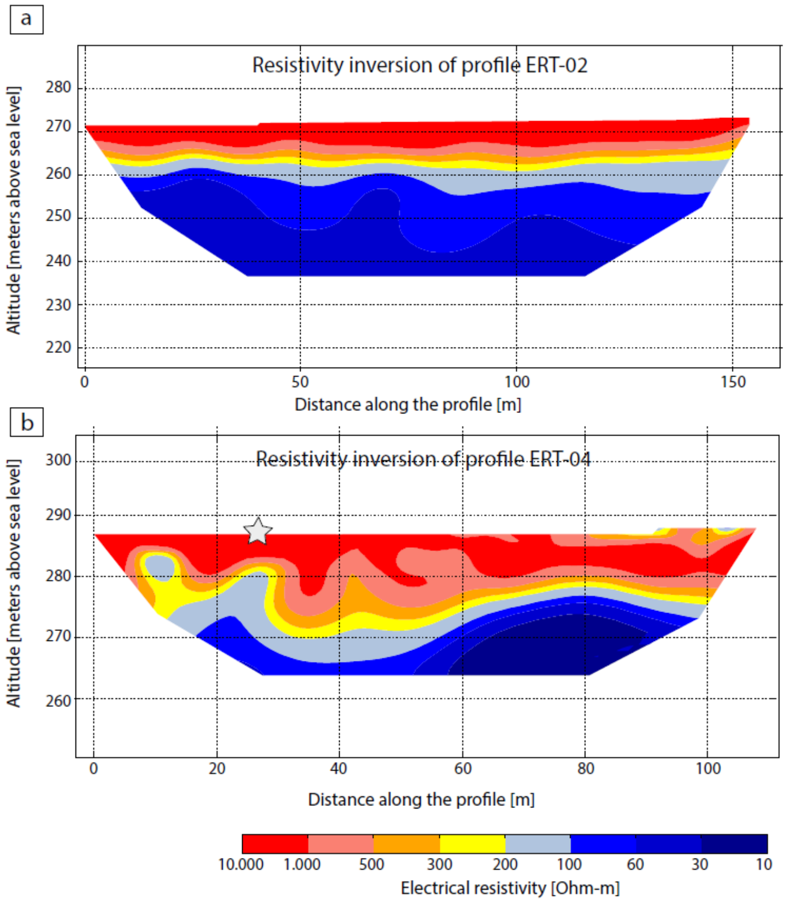

Figure 5: Results of the inversion of the electrical resistivity tomographies. Both profiles have the same color bar. None vertical exaggeration was done. a) ERT-02 inversion, profile close to the river used for groundwater table calibration. b) ERT-04 inversion, profile inside the school used to define the borehole position. The grey start symbolize the position of the borehole.

In order to determine the optimal drilling point, we deployed three ERT arrays inside the school area (ERT03, ERT04, ERT07). In Figure 5b, we present the ERT04 where the borehole was successfully drilled. We only present this profile to avoid excess of details and unnecessary information for the aim of this work (show the steps of this project and the design and installation of the heating system). In ERT-04, the electrical resistivity range expected for groundwater (between 200 and 30 Ωm) has a variable shape, but it is mostly restricted to 270 – 280 m.a.s.l. The shallower segment of this limit is observed between 10 and 20 m of the distance along the profile, we selected this point to carry out the extraction borehole (white start in Figure 5b).

Considering the geophysical interpretation, we expected to find the groundwater table at 7 m depth. This was confirmed to be relatively accurate by the drilling stage where the real water table was found at 9 m depth.

The majority of the TEM surveys were consistent with the ERT results. However, several of these surveys present a high level of noise when performed within urban areas (e.g. TEM 1, TEM 2 and TEM 3 above the school). TEM surveys that have stable response curve are always located in unurbanized areas (e.g. TEM 05 and TEM 06). Therefore, for urban areas ERT methodology seems to be more useful than TEM. Noise and temporally unstable solutions increase the uncertainty of TEM, and for this reason, these results were not used to define the drilling point.

2.2 Thermal insulation

The walls of each pavilion are made of different materials (concrete, partitions or structural insulated panel) and therefore, a detailed inspection of each space was made. Although the building did not have a bad thermal insulation (with double-glazing in almost all openings, walls and roofs covered with thermal insulation, etc.), it still had flaws. A thermographic inspection was also performed to find thermal bridges that reduced the level of insulation in the classrooms.

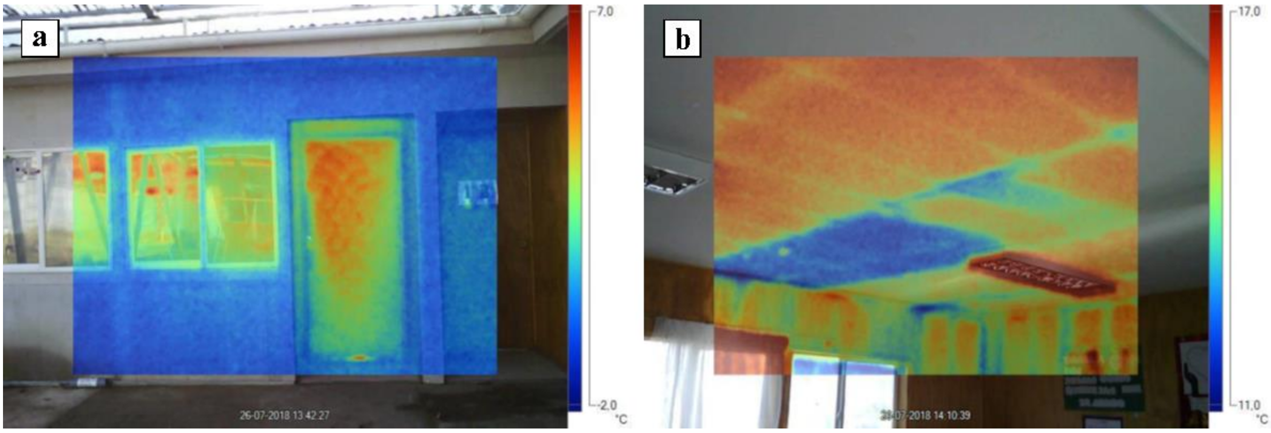

Figure 6: Thermographic images. Zones with different color shows thermal bridges. a) Thermal losses through the door. b) Thermal losses through the celling by poorly distributed insulation.

While there are documents that regulate schools' lighting levels, temperature and ventilation, Chile does not have norms that regulate educational buildings thermal insulation. The only regulated division is the residential sector by the General Ordinance of Urbanism and Constructions (Ordenanza General de Urbanismo y Construcciones, OGUC). Additionally for Coyhaique, the Coyhaique Atmospheric Decontamination Plan (Plan de Descontaminación Atmosférica de Coyhaique, PDA Coyhaique), also establishes insulation criteria for housing infrastructure (Agencia Chilena de Eficiencia Energética, 2012).

A third document was taken as an insulation reference, which imposes greater requirements that are more in accordance with other countries standards, corresponding to Ministry of Public Works (MOP)'s Standardized Terms of Reference (Términos de Referencia Estandarizados, TDRe) for new projects.

In order to adjust to the isolation budget (fund apart from the one awarded by CEGA), two insulation levels improvements were presented. One corresponds to the necessary insulation, which was used to calculate the thermal demand, but does not comply with what is stipulated by the TDRe. The other corresponds to the recommended insulation that complies with the TDRe, but requires a bigger budget. The latter was selected to be implemented, with the acquisition of another fund. In Figure 7, we show the three average insulation levels for the structures of the spaces to be heated, as well the total surface area of each structure.

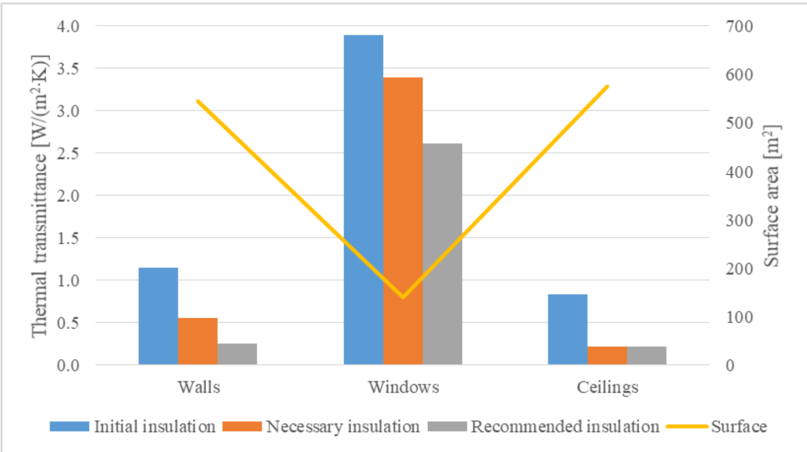

Figure 7: Average thermal insulation for walls, windows and ceilings. Recommended insulation based on (Ministerio de Obras Públicas, 2011).

Ceilings insulation was prioritized for being more cost-effective. Additionally, external doors changes were indicated as necessary. Considering these values, it was possible to calculate the building thermal demand.

2.3 Thermal demand

The thermal demand of the spaces is obtained through analytical calculations based on the following equation:

$$\dot{Q}_{metabolism} + \dot{Q}_{heater} = \dot{Q}_{wall} + \dot{Q}_{window} + \dot{Q}_{ceiling} + \dot{Q}_{floor} + \dot{Q}_{ventilation} \quad (3)$$

Where $\dot{Q}_{metabolism}$, $\dot{Q}_{heater}$, $\dot{Q}_{wall}$, $\dot{Q}_{window}$, $\dot{Q}_{ceiling}$, $\dot{Q}_{floor}$, $\dot{Q}_{ventilation}$ are classroom people metabolic thermal inputs; required heater power; walls, windows, ceilings, floors and ventilations thermal losses; respectively. Solar contribution was not considered since it is only a heating system. Omitting this value allows to slightly oversize the installation, ensuring a correct heat supply.

Metabolic thermal input corresponds to the transformation of energy by metabolic activities of the body. Considering input of each student as the heat generated by a person at rest, the metabolic contribution of people per room is:

$$\dot{Q}_{metabolism} = n \cdot MET \cdot BSA \quad (4)$$

Where n is the number of people inside classroom, MET is the heat generated by a person at rest equivalent to 58.2 W/m^2 (Agencia Chilena de Eficiencia Energética, 2012), and BSA is the body surface area equivalent to 1.7 m^2 for people between 13 and 18 years old (Georgiev, n.d.).

Losses through walls, windows and ceiling were calculated according to:

$$\dot{Q} = U \cdot A \cdot (T_{int} - T_{ext}) \quad (5)$$

Where U, A, T_{int}, T_{ext} are the material thermal transmittance, the object measured surface, the temperature inside each classroom and the outside temperature, respectively. Thermal transmittance was calculated using the thickness and materials properties showed in NCh853-2007 (Instituto Nacional de Normalización, 2007). The temperature inside each classroom is set to 20 °C (Agencia Chilena de Eficiencia Energética, 2012), and the outside temperature data was gathered from El Claro weather station (INIA, n.d.). These measurements were made every hour, throughout a year, starting at January 1st 2017.

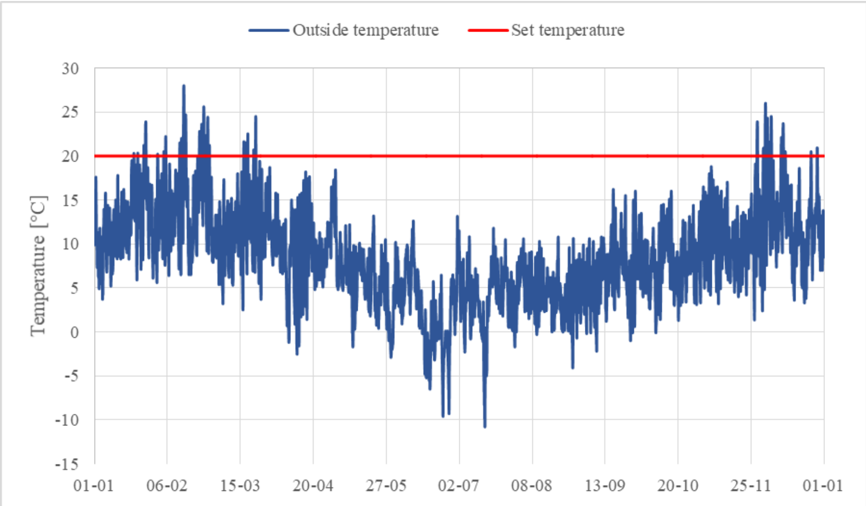

Figure 8: Air temperature in Coyhaique during 2017 and set temperature. Made based on (INIA, n.d.).

Floor heat loss is calculated following the equation (Instituto Nacional de Normalización, 2007):

$$\dot{Q}_{floor} = K_l \cdot P \cdot (T_{int} - T_{ext}) \quad (6)$$

Where K_l is the linear thermal transmittance equal to 1.4 W/(m·K) and P is the external perimeter of the floor considered.

Considering that classrooms have a large number of people, a correct ventilation is necessary to ensure indoor air quality and health, as well as a control of relative humidity. This also helps reducing the levels of CO_2 produced by the breathing of the occupants. A simplified equation from (Valera et al., 2008) is used to calculate ventilations thermal losses:

$$\dot{Q}_{ventilation} = C_{air} \cdot \rho_{air} \cdot c_{p\,air} \cdot (T_{int} - T_{ext}) \quad (7)$$

Where C_{air} is the air renewal, considered equal to 5 L/s per person during class period and equal to 1.5 air changes per hour the rest of the time, caused by not controlled infiltrations in small slits or other openings (Ministerio de Obras Públicas, 2011); ρ_{air} is the air density; and $c_{p\,air}$ is the air specific heat at constant pressure.

In order to determine the thermal demand, only active class periods were considered. Also, we considered zero demand during nights, weekends or holidays (summer holiday between December to March, winter holiday during July). Months of holidays therefore have a lower or no demand. The annual thermal demand was estimated around 29,000 kWh_t and monthly losses are shown in Figure 9. It should be noted that Figure 9 does not show the metabolic thermal input, hence the difference with the annual demand.

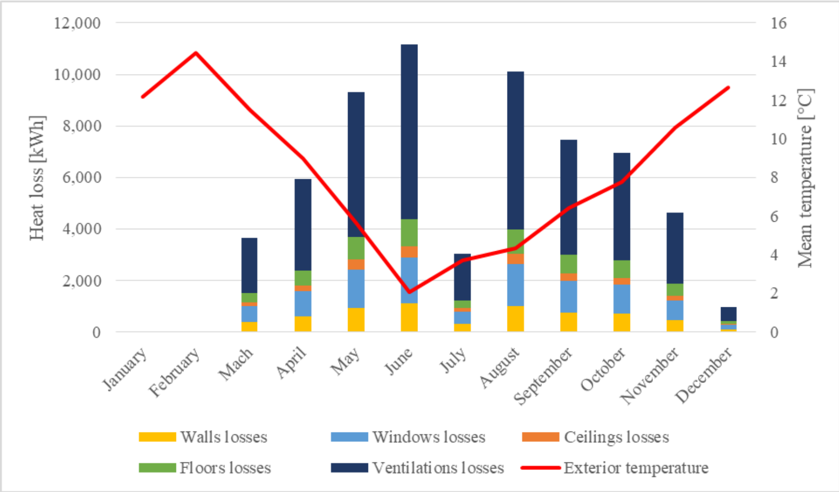

Figure 9: Monthly heat losses through the different structures and mean air temperature in Coyhaique during 2017 based on (INIA, n.d.).

On the other hand, thermal power required is estimated to cover most of the demand, not taking account punctual peaks, equal to 50 kW_t, which implies a minimum well flow of 2.8 L/s using equations 1 and 2. Based on this, the equipment was selected and installed.

3. FINAL INSTALATION

3.1 Borehole drilling

The geothermal system implementation begun with the drilling of two boreholes during October 2018, one for extraction and one for reinjection of groundwater. The extraction well has a 20 cm (8 in) diameter and 36 m depth, while the reinjection well has a 15 cm (6 in) diameter and 24 m depth. Borehole depths were planned to extract the necessary water flow based on the school thermal power demand. To prevent interference between the two boreholes, we spaced them 50 m from each other, with 1 m of ground unevenness. Reverse circulation drilling method was used for borehole drilling (Figure 10a) and was made by the only company in the region offering this services, with an approximate cost of USD$45,000. Bargaining a better price couldn't be made, since we had not other offers available. To prevent the well from collapsing, steel pipes were welded (Figure 10b) and buried as drilling. Both boreholes were covered with an inspection chamber and all connections were made underground (Figure 10c).

Figure 10: Boreholes drilling. a) Drill extracting ground water while drilling. b) Driller welding two steel pipes. c) Borehole final state.

Static water level was found at 9.1 m depth during the drilling process. A constant-rate and variable-rate pumping tests were carried out to estimate the water flow available to be used in the geothermal system. Constant-rate test at 10 L/s was performed during over 20 h and showed a dynamic level of 12.2 m, with a recovery time around 30 s. Variable test was performed with different water flow rates (from 1 to 20 L/s), with a duration of 25 min each (Figure 11). At 20 L/s, the borehole still had the capacity to extract water with the submersible pump placed at 30 m, exceeding by far minimum flow needed, allowing to have a heating system of over 350 kW_t with a 3.4 COP. The final installation extracts around 5 L/s at approximately 10 °C.

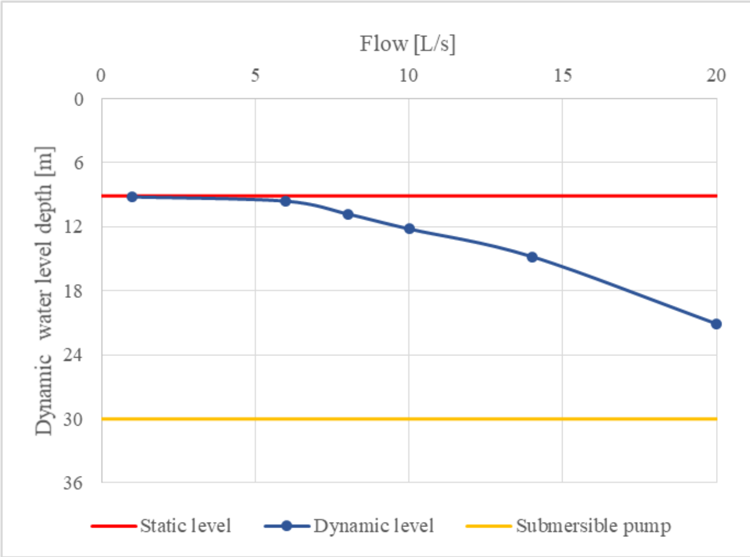

Figure 11: Variable-rate pumping test results.

During the drilling process, samples of expelled detritus were gathered every 3 m to describe and classify them based on their granulometry. This allows to understand the permeable levels and their relationship with slotted segments of the extraction well. Considering the dynamic and static levels, along with the granulometric analysis, the presence of a variable thickness unconfined aquifer is suggested above 9 m depth. This aquifer in turn, overlaps a semi confined aquifer between two levels with a high clay proportion between 9 and 15 m in the top, and 30 and 36 m at the bottom. Figure 12 shows the extraction borehole profile based on the expelled detritus, the aquifers location and the slotted pipe section.

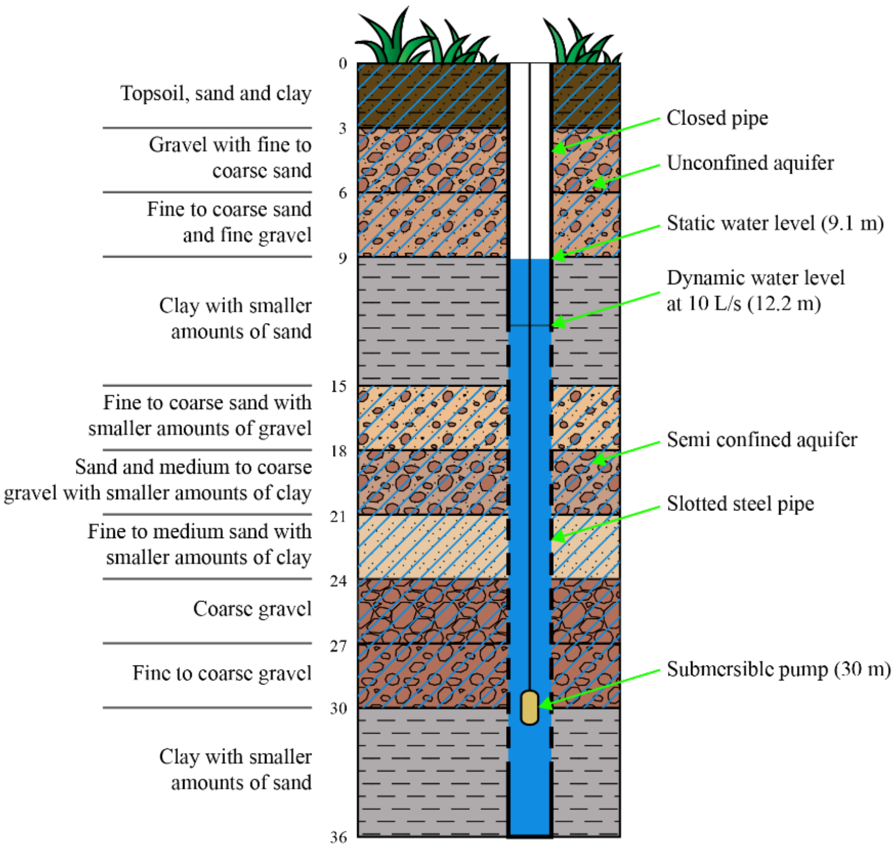

Figure 12: Extraction borehole profile. Dashed line indicates slotted pipe section. Blue striped area indicates aquifers location.

Unfortunately, the reinjection well showed more impermeable levels than the extraction well, so reinjection capacity is reduced (1 L/s). This forced us to pour most of the water back into the river (40 m away from the well) through a drain designed to operate in case of overflows.

3.2 Final installation

Two 25 kW_t geothermal heat pumps were installed in the mechanical room. Since groundwater passes through an external heat exchanger instead of going to the heat pumps (avoiding damage by fine-grained sediments), the cold circuit temperature is around 5 – 7 °C. Considering this temperature and setting the hot circuit temperature to 45 °C, the heat pumps COP is 3.4 (ecoForest, 2018).

While most of the school was heated with radiators, using fan coils is more efficient despite having an additional electrical consumption (to power the fans). This is because radiators operate at higher temperatures (over 60 °C), which decrease heat pumps efficiency (COP below 3) and thus produce higher electrical consumption. Radiators could operate at lower temperatures but require a much higher surface to deliver the same heat, making it impractical. Greater efficiency would have been achieved by using underfloor heating, but it was discarded because it requires a much higher investment in already built infrastructure.

Equipment installation was made during summer holiday in 2019, between January and February, but its operation began in May due to a delay in the electric installation. All equipment and most of the materials were imported from other regions or countries, having to wait for the transport time of missing materials. At the same time the installation company came from other region, due to the lack of capacitate personnel in the zone. Since installation was made during summer, weather conditions did not delay the work progress, unlike the wells drilling.

The equipment consist in two geothermal heat pumps, thirteen fan coils, two radiators, one 1.500 L buffer vessel sized based on (Homemicro, 2016), an other equipment. Buffer is used to capture residual heat on shutdown to improve the system efficiency. Fan coils are outside the mechanical room and inside each classroom (Figure 13). Original radiators and firewood stoves inside classrooms were not removed so they could work like a backup in case the geothermal system fails during the first operation year. Equipment and installation implied an investment of approximately USD$100,000. On the other hand, annual operational cost was estimated around USD$4,300.

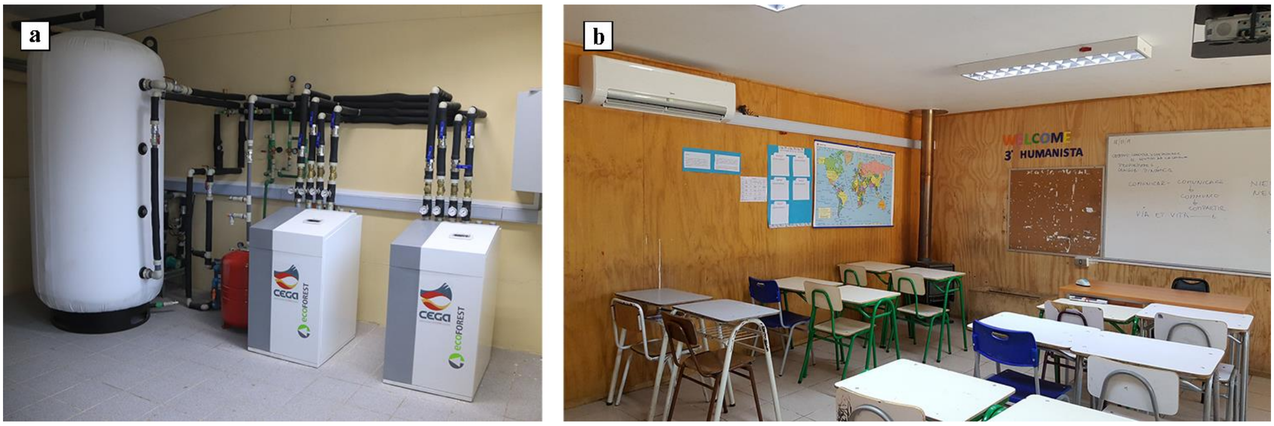

Figure 13: Installation pictures. a) Geothermal heat pumps, buffer vessel and others equipment inside the mechanical room. b) Fan coil inside a classroom.

This system will avoid burning around 100 m^3 of firewood per year, which implies an annual emission reduction of 500 – 1,000 kg of PM10 and PM2.5 each (Universidad de Concepción, 2013).

4. CONCLUSION

Geophysical prospection was useful to ensure groundwater availability and to locate the extraction well closer to the water table. Similar conditions to the school are present in the area enclosed between the Simpson and Claro Rivers near the city, having an opportunity to implement more groundwater heat pump systems. These studies require a comparison point to calibrate the measurements. These could be exploration boreholes, or like in this case, a river. Despite having a lower penetration depth than TEM, ERT it is better for groundwater searching in urban areas because it has less noise.

A thermal insulation study is necessary to determinate the thermal demand, equipment sizes and insulations shortcomings. While thermography inspection was just qualitative, it allowed mapping the zones were more insulation was required. The lack of a national thermal insulation norm for schools makes it difficult to maintain a standard in this area. The necessary insulation level resulted in a demand reduction of around 40% when compared with the initial level. This leaded to a reduction of equipment sizes, reducing the inversion in this area.

Since the Aysén region is an isolated territory, the final installation was more challenging compared with other regions. The presence of only one drilling company makes it difficult to quote more options, implying a more expensive service. On the other hand, the cold and rainy weather of the region, along with the low materials stock, delayed most of the tasks. Despite this, the system was successfully implemented and will be tested when the students return from holidays.

Geothermal heat pumps have the potential for replacing firewood as a heat source in urbans areas with a similar operational cost, with the advantage of zero particulate matter local emissions. However, with the actual market and given the necessary investment, only major building as schools, hospitals, and others public buildings could afford the implementation of these systems. State funding is necessary to implement the technology and subsequently, increase the demand and stimulating to new entrepreneurs to install these systems. This would create the market environment necessary to reduce the costs associated with this technology.

REFERENCES

Agencia Chilena de Eficiencia Energética: Guía de Eficiencia Energética para Establecimientos Educacionales, (2012).

CANMET Energy Technology Centre: Ground-Source Heat Pump Project Analysis. In Clean Energy Project Analysis, *RETScreen Engineering & Cases Textbook*, (2005).

ecoForest: Fichas técnicas ecoGEO, (2018), 7-8.

Georgiev, G.: Body Surface Area Calculator, retrieved July 9, 2019, from https://www.gigacalculator.com/calculators/bsa-calculator.php, (n.d.).

Hepp, C., Reyes, C., & Muñoz, R.: Análisis de datos históricos de cinco estaciones meteorológicas de la región de Aysén (Patagonia). *Boletín Técnico N°365*, retrieved from www.inia.cl, (2018).

Homemicro: Thermal Storage Vessel Sizing, retrieved from www.homemicro.co.uk/lzc_vessel.html, (2016).

INE Chile: Resultados CENSO 2017, retrieved July 5, 2019, from http://resultados.censo2017.cl/Region?R=R11, (2017).

INIA: Agromet Estaciones. Retrieved July 11, 2019, from http://agromet.inia.cl/estaciones.php, (n.d.).

Instituto Nacional de Normalización: NCh853, Santiago, Chile, (2007).

IQAir: 2018 World Air Quality Report, retrieved from http://aqicn.org/city/mexico/mexico/camarones/, (2018).

Kirsch, R.: Groundwater Geophysics, *Groundwater Geophysics edited by Reinhard Kirsch*, Berlin: Springer, 2009. ISBN: 978-3-540-88404-0. https://doi.org/10.1007/3-540-29387-6, (2009).

Ministerio de Energía: Energía 2050, Política Energética Región de Aysén, retrieved from http://www.mienergia.cl/sites/default/files/archivos/politica-energetica-aysen-2050.pdf, (2018).

Ministerio de Obras Públicas: TDRe, Santiago, Chile, (2011).

Rees, S. J.: An introduction to ground-source heat pump technology, *Advances in Ground-Source Heat Pump Systems*, https://doi.org/10.1016/B978-0-08-100311-4.00001-7, (2016), 1–25.

Telford, W. M., Geldart, L. P., & Sheriff, R. E.: Telford - Applied Geophysics, https://doi.org/10.1180/minmag.1982.046.341.32, (1990), 1–760.

Universidad de Concepción: Calefacción distrital con biomasa en Chile - Evaluación del potencial de reducción de emisiones en Osorno, Concepción, Chile, (2013).

Valera, D., Molina, F., & Álvarez, A.: Ahorro y Eficiencia Energética en Invernaderos. Retrieved from https://www.idae.es/uploads/documentos/documentos_10995_Agr07_AyEE_en_invernaderos_A2008_9e4c63f5.pdf, (2008).