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KIT M.Sc. in Mechanical Engineering

METHODOLOGY FOR ENERGETIC AND ECONOMIC EVALUATION FOR THE GEOTHERMAL HEAT EXPLOITATION IN AN INDUSTRIAL FACILITY

Federico José Wagner
Industrial Engineer
Universidad Nacional de Tucumán

Tutor
Dr Dietmar Kuhn

Co-Tutor
Ing. Martín Fraguío

Examiners
Prof. Dr-Ing. Andreas Class KIT/ ITES
Prof. Dr. Thomas Schulenberg KIT/ ITES

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Abstract

This work aims to analyse the use of low enthalpy geothermal heat in Bahía Blanca by evaluating different alternatives when using it in a specific project.

In Bahía Blanca, Argentina, several boreholes with geothermal water have been used for many years. Although there are ageing wells in this area, many of which are proof of the existing considerable geothermal potential, only a few are deemed heat sources.

The first section introduces general concepts for the contextualisation of the document. Then, the second section details all the performed methodology and an explanation about the selection of the industrial case is given. Then, the industrial system and pipelines are presented, followed by a description of the mass and energy balances. Later, the heat pump calculous, economic evaluation and CO_2 footprint analysis procedures are presented.

Finally, the fourth section presents all the obtained results in graphics and tables, and at the end, the conclusions are assessed.

Motivation

The region of Bahía Blanca presents a promising future development because of its strategic location and capable infrastructure. However, freshwater represents a scarce resource currently, and this water's shortage needs to be solved for the region's economic development.

The underground water exploitation in the area dates back to the foundation of the first settlements in the region. In the beginning, most of them had the aim to provide freshwater. Nevertheless, the pioneers' inhabitants of the growing city recognized the potential of having such a heat content in the potable water in this windy region of Argentina. Therefore, some of the first users initiated to take advantage of the heat.

However, with the pass of time, a new dam for water provision in the city was constructed, and thus the underground water was no anymore the primary water source for the citizens. Additionally, the relatively accessible prices for electricity and mainly natural gas in the area fomented to a decrease in interest in the low-enthalpy heat content from the geothermal wells.

The sum of these factors ended with low maintenance, and in some cases, the wells were permanently closed. Therefore, it can be considered that this beneficial source of potable water and renewable energy is not thoroughly utilized.

Therefore, this master thesis started with the question: What could be done with those geothermal wells?

Then, this document presents a methodology to evaluate such a project for the region, including heat pumps technology that enables low-enthalpy heating and cooling use, increasing the system's efficiency.

Different cases are compared to assess the convivence for geothermal water utilization through economic analysis and CO_2 footprint evaluation. Hopefully, this work helps evaluate this resource and foment future sustainable projects.

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List of abbreviations and symbols

$\dot{m}_C$ Air mass flow C [kg/h] SEGEMAR Geologic and Mining Service of Argentina

United States

Environmental Protection Agency

F_C Air volumetric flow C

[m^3/h] EPA

$\dot{Q}_1$ Heat transfer rate 1 [kW] INA Water National Institute of Argentina

GHE Green House Emissions CREEBBA Economic Studies Centre of Bahía Blanca

NPV Net Present Value ABSA Waters of Buenos Aires Inc.

Argentinian National Institute of Statistics and Censuses

UNS National University of the South INDEC

CP Specific heat capacity SHP Deep Hydrothermal System of Bahía Blanca

GT Geothermal LCV Lower Calorific Value

1 Introduction

In this first section, a context introduction will give the reader some preliminary explanation about geothermal exploitation and its possible fields of application. Then, the city of Bahía Blanca will be presented with short references to its history. This presentation will help understand the origins of the existing geothermal aquifers and current operative geothermal wells. In addition, the freshwater provision system will be described to size the water importance in the region.

1.1 Geothermal as an energy source

The Earth is composed of different geological layers. Starting from the surface, we find the first — and thin — Earth crust, followed by the mantle, the outer and inner cores, respectively. According to (Litasov & Shatskiy, 2015), the surface temperature is around 14 [ºC], but if deeper excavated, the inner core temperatures can reach up to 5500 [ºC]; i.e., the deeper the drill, the higher the temperature.

These high temperatures could be helpful to be used on the Earth's surface, but because of the great depth in which they are located, they are mostly unavailable for human usage. The challenge when retrieving this accumulated energy is not only the great depth to be excavated but also the pressure, in which up to 360 [GPa] can be easily reached.

The Earth's inner core is the innermost part of our planet, whose radius is approximately 1220 [km] and whose material is a solid iron-nickel alloy. Then, the outer core has a thickness of 2250 [km], whose temperature is around 4000 [ºC], and its composition is primarily molten iron. Due to the convection in the outer core and the interaction of the Earth rotation, the Earth's magnetic field is generated. (Stober & Bucher, 2014)

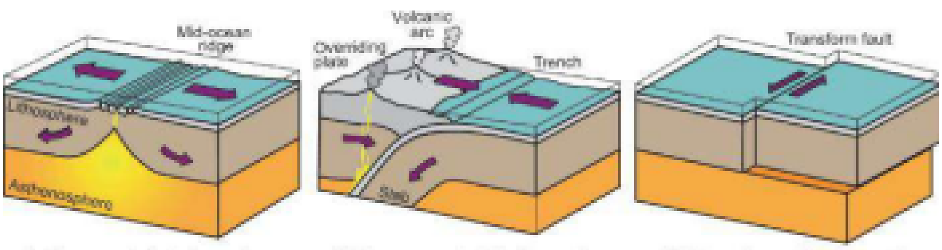
Owing to the crystallization heat caused by the slow cooling process of the core, sufficient energy to heat the Earth's mantle is harnessed (Hirose, et al., 2017). This natural process leads to a difference in density which causes a convective movement of the ductile material over millions of years. In other words, hot material rises, and cold material sinks. This part of the mantle is known as the Asthenosphere.

The Lithosphere nestles just above that and includes the uppermost part of the mantle and the Earth's crust. Its size varies in a few kilometres at mid-ocean ridges, up to 200 [km] on the continental areas. The Lithosphere can be considered to be floating on the ductile Asthenosphere. The dynamism and movement of this layer are known as plate tectonics and can be sorted into three categories (Frisch, Meschede, & Blakey, 2011).

Converging plates, where two plates may either collide and form mountains ranges, or, conversely, one oceanic plate slides below another plate generating an oceanic trench and volcanic mountain ranges.

Diverging plates result in rift events or mid-ocean ridges where ascending magma cools down and forms a new oceanic crust.

Relative movements are transverse to the plate boundaries. These movements have in common that they are a source of earthquakes and, in many cases, volcanic activity.



a) Divergent plate boundary b) Convergent plate boundary b) Transform plate boundary

Figure 1: Dynamism and movements of Earth's layers. Source: (Acocella, 2021)

1.2 Internal and External Sources of Energy of the Earth

The Earth receives considerable amounts of energy from both external and internal sources. In order to provide an illustrative comparison, the global production of primary energy in the year 2015 was used. This amount was 567 x 1018 [J]. (International Renewable Energy Agency (IRENA), 2017)

Naturally, the most prominent external energy source of the Earth is the sun. The incident energy of solar rays for one day is 1.5 x 1022 [J], which corresponds to about 26 years' worth of the global production of the primary energy demand in 2015. In other words, the irradiation of one week surprisingly adds up to the expected cumulative primary energy requirements for the entire current century.

Nevertheless, only regrettably small amounts of this irradiated solar energy are converted into forms of energy that can be stored relatively permanently on the Earth, mainly as fossil fuels.

The interior of the Earth provides scorching heat from four primary sources:

• Radiogenic heat from the decay of unstable, radioactive isotopes;
• Original heat, i.e., the heat content of the infant Earth immediately after formation;

• The potential energy released as heat during the creation of new crust, the enrichment of heavy metals in the Earth's mantle or the formation of the iron core of the Earth; • Released frictional heat from elastic energy in earthquakes.

The largest internal energy source of the Earth is a result of radioactive decay of the natural isotopes uranium [^{238}U, ^{235}U], thorium [^{232}Th] and potassium [^{40}K] in the rocks of the Earth's crust.

The heat produced by this source is 8.6 × 1020 [J] within one year. Theoretically, it could cover the global production of primary energy, compared to the year 2015 (Clasuer & Heinloth, 2009). However, this energy harvest is technically impossible.

In addition, due to the difference in temperature in the Earth's inner core and crust, a continuous heat transfer occurs. This terrestrial heat flux is approximately 0.065 [W/m^2] and leads, in the long term, to a decrease in temperature in the Earth. Nevertheless, only around 30 % of this heat flux measured at the surface is coming from the Earth's core, whereas the remaining 70 % comes from the Earth's crust.

Part of this heat is stored in the Earth's crust within all the layers and different materials composing the Earth's anatomy.

1.3 Concepts of geothermal energy

The use of thermal water is as old as civilization itself. The Greeks and Romans left numerous examples of its application in district heating and traditional baths or public baths. More contemporarily, in 1904 specifically, Prince Piero Ginori Conti promoted the construction of the first 250 [kW] power plant that came into operation in 1913 in Lardarello, Italy.

In accordance to the International Renewable Energy Agency, geothermal energy is the heat given off from the core of the earth (International Renewable Energy Agency (IRENA), 2017).

In regions where the earth's crust has a relatively stable behaviour, such as that offered by the continental plates, some areas present heat concentration with flows that have gradients of the order of 30 [°C] to 50 [°C] per kilometre of depth. If favourable structures exist in these regions and appropriate perforations can be made, it is viable to obtain fluids with temperatures in the order of 50 [°C] to 100 [°C] at relatively shallow depths (Pesce, Mas, Gonzalez, & Vazquez, 1995).

In addition, especially where continental plates drift together or volcanic activity occurs, much higher temperatures in shallow depths can be found. Examples of this are Larderello, Castelnuovo

and Serrazzano in Italy, where at a maximal depth of 1200 [m], even 260 [°C] could be found (Minissale, 1991).

Geothermal energy can be used directly, without further conversion, as heat source. The direct application of geothermal heat is called direct use. Alternatively, geothermal heat can also be converted into other different types of energy at the expense of some energy for conversion. For instance, electric power generation requires conversion into electricity.

1.3.1 Types of geothermal energy use

Geothermal systems can be schematically described as the convection of water in the upper part of the earth's crust, which, in a confined space, transfers heat from a heat source to the surface. The heat source, the reservoir, the recharge area, and the connection pathways through which the surface water enters the reservoir (which most cases emerge back to the surface) constitute the fundamental parts of a hydrothermal system. A seal, made up of geological units or structures that act as a waterproof cover, closes the system, favouring the concentration of heat.

Within a hydrothermal system, the permeable rocks constitute the reservoir so that the extraction of fluids is restricted to specific sectors of the system. These producing areas are called geothermal fields, and geothermal fields are commonly classified or divided by a series of descriptive terms.

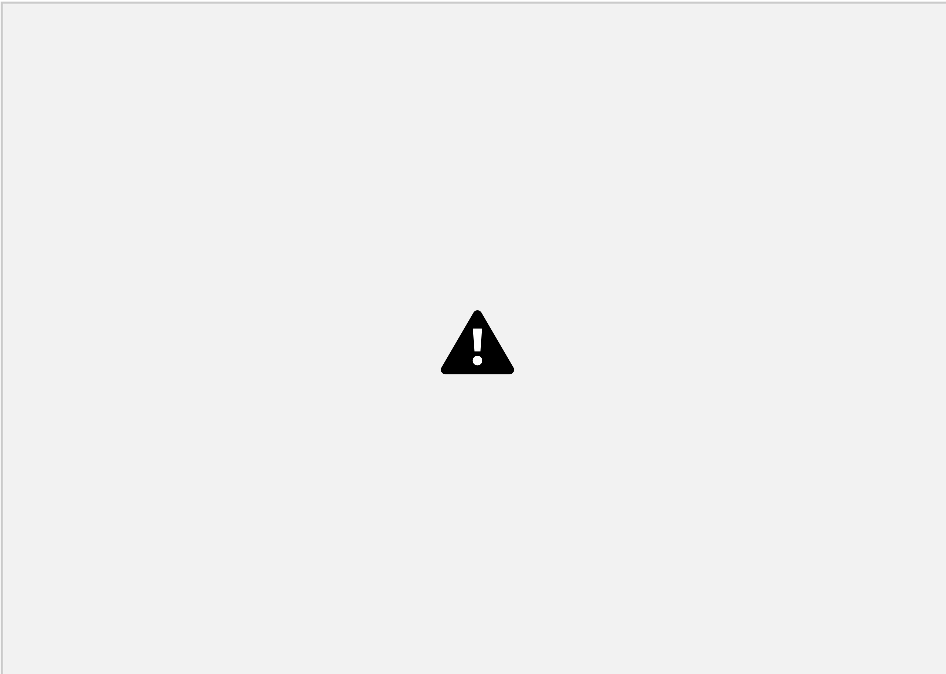


Figure 2: Favourable and unfavourable geothermal fields classification. Source: (Badea, 2021)

Geothermal resources have been classified as low, medium, and high enthalpy resources according to their reservoir temperatures, as shown in the Figure 2. In addition, if the depth of the reservoir is considered, the geothermal potential of the fields could be classified as “Normal”, favourable, or very favourable. The higher the temperature at a shallow depth, the more advantageous the field.

1.4 Geothermal energy in Argentina

In Argentina, numerous areas with geothermal potential can be pointed out:

• The Andean range, with volcanic systems in the west;

• The El Salado basin in the province of Buenos Aires and,

- The Chacoparanense basin, encompassing the provinces of Santiago del Estero, Chaco, Formosa, Santa Fe, Entre Ríos, Corrientes and Missiones, as well as parts of Paraguay, Uruguay and Brazil;
- The Colorado basin in Bahía Blanca

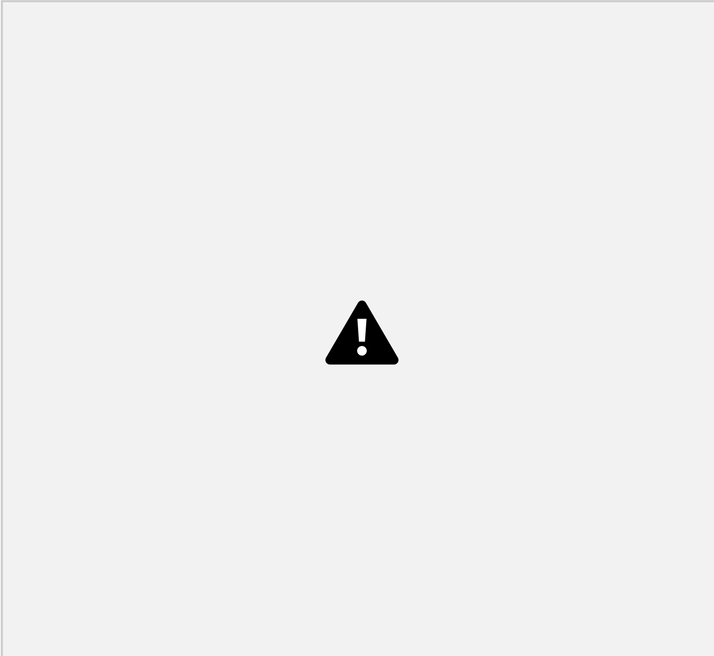


Figure 3: Geothermal fields in Argentina. Source: (Pesce, Argentina Country Update, 2015)

The locations where projects of geothermal exploitation take place in Argentina are portrayed in the picture above (Pesce, Argentina Country Update, 2015).

The high-enthalpy projects are within the Andes range, except Termas de Río Hondo, at the border between Santiago del Estero and Tucumán, where a strong heat anomaly is found, with a geothermal gradient between 3.5 to 4 times higher above average.

Almost all projects in the Chacoparanense and El Salado basins provide low-enthalpy sources.

In Argentina, there are provinces where geothermal projects are in different stages of study. These include: Catamarca, Jujuy, La Rioja, Mendoza, Neuquén, Salta, San Juan and Tucumán. Gubinelli points out that out of these provinces, only four have geothermal projects which are already in the stage of feasibility studies; yielding the following results (Gubinelli, 2017) :

- Jujuy Province, volcano Tuzgle, estimated capacity 20 to 30 [Mwe].
- Neuquén Pr., volcano Copahue, confirmed capacity 30 [Mwe].
- Salta Pr., geothermal project Falla Tocomar, estimated capacity 20 to 30 [Mwe]. • San Juan Pr., geothermal project Los Despoblados, estimated capacity 15 to 20 [Mwe].

Despite these positive prospects, little advance has been made in recent years, as the example of Copahue shows, where the first geothermal power plant was a 670 [kW] pilot project. Drillings were made in the 1970s, containing four wells between 954 [m] to 1414 [m] and temperatures in a range of 220 [°C] to 250 [°C]. (ADI-NQN, 2014)

Regardless of the promising results and good logistical conditions, the plant only operated between 1988 to 1997. Attempts by the government of Neuquén since 2009 to promote and reactivate the project have so far been unsuccessful. (Pesce, Argentina Country Update, 2015)

1.5 Geothermal potential of Bahía Blanca

The city of Bahía Blanca is the head of the district, which holds the same name, and it is geographically located to the southwest of the province of Buenos Aires. The Bahía Blanca district, in addition to the central city, includes the towns of Cabildo, General Daniel Cerri and Ingeniero White.

According to the last population census carried out in 2010, the population of the city of Bahía Blanca amounts to 301 572 inhabitants, observing a relative intercensal increase of 5.9 % compared to the 2001 census, when the population reached 284 776 inhabitants.

Bahía Blanca, due to its population size, ranks as the seventeenth most populated centre in Argentina. From the geographical point of view, it is the second of the country's coastal towns, behind Mar del Plata (Municipalidad de Bahía Blanca, 2020).

1.5.1 History of Bahía Blanca

In its beginnings, this village located in the southwest of Buenos Aires was nothing more than an almost exclusively military settlement. The appearance of the railroad in 1884 constitutes a factor of national integration and a multiplier of the population process. Very soon, in 1885, the iron dock was also built in the already incipient port, providing a natural outlet for the Buenos Aires, Pampa and Rio Negro regions.

The expansion of livestock, agricultural production, the increase in immigration, the improvement of communications and transportation were also factors for the city growth. Thus, a commercial, industrial, financial, and service infrastructure was formed in the region.

Constant growth over the years meant that, in 1980, the National Institute of Statistics and Censuses (INDEC) considered the Municipalities of Coronel Rosales and Bahía Blanca as a metropolitan urban grouping. At present, the Bahía Blanca Area is the fourth-largest urban agglomerations in Buenos Aires and the second of the coastal agglomerations of Argentina, only surpassed by Mar del Plata. (Municipalidad de Bahía Blanca, 2020)

1.5.2 Description of water sources in Bahía Blanca

Of the total waters of the planet, 97.6 % are salty waters of the oceans; polar ice accounts for 1.9 %; groundwater, 0.5 %; freshwater from lakes, rivers, and streams only 0.009 % and saltwater from lakes 0.008 %. The small remaining percentage is distributed as soil moisture and water vapour in the atmosphere (Dr. Bonorino, Dr. Carrica, & Lic. Lafont).

From the preceding, it can be deduced that — by volume, chemical quality, availability and possibilities of use — groundwater constitutes the most crucial source of water on the planet for human supply.

Groundwater is part of the hydrological cycle, and it is a fraction of rainwater that infiltrates the soil, saturates it and recharges it to saturated levels at depth. Groundwater forms a generally continuous system made up of the ground materials (gravel, sand, silt, clay, and their mixtures) and their water-filled pore spaces, the whole being generically named the saturated zone. The levels in the saturated zone with the highest permeability allow the water to be easily extracted, are called aquifers.

The groundwater reserves of all the basins studied in Argentina reach 1.5 million [hm^3]. The state makes more than 60 000 groundwater exploitation wells (national, provincial, and municipal), and more than 300 000 are made by individuals, especially for irrigation and industry.

Approximately 50 % of the population of the Argentine Republic is supplied with underground water, mainly in rural areas, although urban conglomerates such as the Buenos Aires suburbs, part of the city of La Plata, Mar del Plata and others.

In the Bahía Blanca area, three principal aquifers can be distinguished:

- **The deep aquifer or Deep Hydrothermal System of Bahía Blanca (SHP)**

It has a continental extension of 3 000 [km^2] (around 50 [km] long and 60 [km] wide). It is located at a depth of approximately 650 [m]. It is characterised by containing hot water (with temperatures between 50 [°C] and 75 [°C]), natural upwelling and high-quality properties that make them marketable as "mineral waters". Initial upwelling flows measured in some catchment works reached very high values.

- **Intermediate aquifer**

It is located at a depth of about 200 [m], and the water is saturating the pores of fine and very fine grain sands. Its waters have a temperature of around 30 [°C] and have natural upwelling in some places. However, their high salt content restricts it only for filling swimming pools, washing facilities or sanitary use.

- **Phreatic aquifer**

It is situated a few meters deep in the city of Bahía Blanca (from 2.5 to 10 [m]), deeper in the north (between 40 and 50 [m]), and at intermediate depths towards the foothills of the Sierras de la Ventana. Its waters are saturating materials consisting of sand and silt. Regarding the chemical quality of groundwater, those located in the urban area of Bahía Blanca are of poor quality because, in addition to being naturally salinized, they are contaminated by percolating from urban cesspools.

However, in contrast to this situation, there are aquifers with waters of excellent chemical quality for human supply in the mountains (Dr. Bonorino, Dr. Carrica, & Lic. Lafont).

1.5.3 Groundwater of Bahía Blanca

For this paper, the most profound aquifer system SHP will be analysed, owing to its properties, which make it suitable for providing water and low enthalpy heat.

The most outstanding characteristics of the SHP are:

- The depth at which it lies, between 500 [m] and 1180 [m]

• The natural upwelling flow, variable between 30 [m^3/h] and 60 [m^3/h] average • The water pressure at the wellhead, or hydraulic potential of the aquifer layer, that reaches between 5 and 10 [atm]

• The quality of its waters, suitable for all use in most of the carried-out wells • The temperature of the water, between 56 [°C] and 74 [°C], allowing the thermal use as a renewable resource

1.5.4 First water sources in Bahía Blanca

In the beginnings of Bahía Blanca, particularly the Deep Hydrothermal System constituted an essential source of water supply. The first drilling carried out reaching SPH was performed at the Argerich station in 1915, and since that moment, many wells have been performed. In those years, the city of Bahía Blanca was supplied with water from 25 SHP wells. Then, in the 1960s, the construction of the Paso de las Piedras dam began and from 1976, when it was inaugurated, the main water supply of Bahía Blanca was replaced.

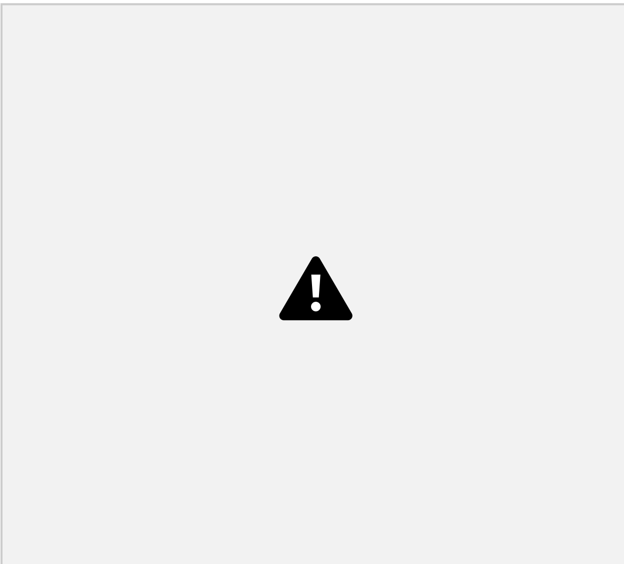
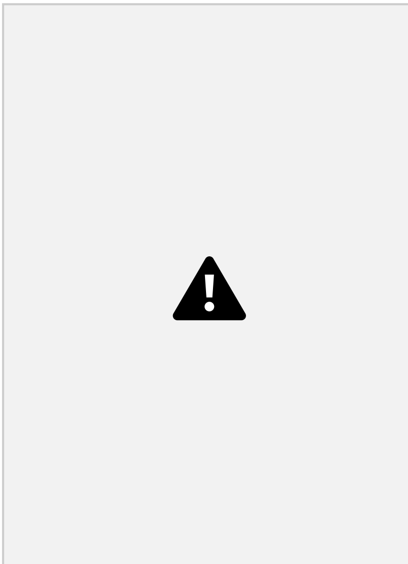



Figure 4: Well digging and current picture of water tank. Source: (Obras y Protagonistas, 2021)

For instance, one well is located on Zelarrayán street and its digging record and tanks are shown in Figure 4. The Aguas Corrientes company built 1953 this new upwelling well. In this case, an initial flow of 300 000 [l/h] was obtained.

The current potable water supply system for the city of Bahía Blanca includes the distribution of water in the towns of Ing. White, General Cerri, Punta Alta and Base Puerto Belgrano, including around 340 000 inhabitants (Dirección Provincial de Servicios Públicos de Agua y Cloacas, 2010).

In addition to the city provision's wells, some wells were also dug in the three military bases in Bahía Blanca. The Naval Air Base Commander Espora, the Puerto Belgrano Naval Base and the Naval Base of Marine Infantry Baterías. Many wells are being used mainly as a freshwater supply in these bases. For this purpose, in most of the cases the water is cooled down by using open tanks releasing the heat into the environment to achieve a moderate temperature. Only a few users, utilizes the well as heat supply, but this heat is not very appreciated because of different technical problems as for example, due to scales incrustation in the pipelines.

In addition, there have also been some well-known cases in which geothermal water was used in industrial processes. One of the most famous cases is the case of the Manera's Pasta Company. This company, founded in 1927, had a water well from which the water and the heat was used in industrial pasta production.

Other examples where the heat was used in industries were the wool factory San Blas, which was settled in 1936, the corned beef factory Corporación Argentina de Productores de Carnes (CAP), which started to work in the year 1903 in General Daniel Cerri (La Nueva, 2006).

Regarding the case of Cerri's plant, this company is no longer working, but its source continues to offer pure and natural water to the neighbours who arrive with their cans at the taps arranged in the place.

Finally, it was not only the industry's case where heat was used but also the case of some significant buildings in the city. One of them was the La Plaza commercial gallery, which was inaugurated in 1961.

1.5.5 Current geothermal water wells use

In the year 2000, a survey was conducted by Servicio Geológico Minero Argentino (SEGEMAR) for all the existing wells in the surroundings of Bahía Blanca. This in-depth survey included, not for all but for almost every well, salient parameters such as depth, geographical coordinates, temperature of the water, level, geological information of the layers, flow and use. The exact location of the wells is shown in Figure 5.

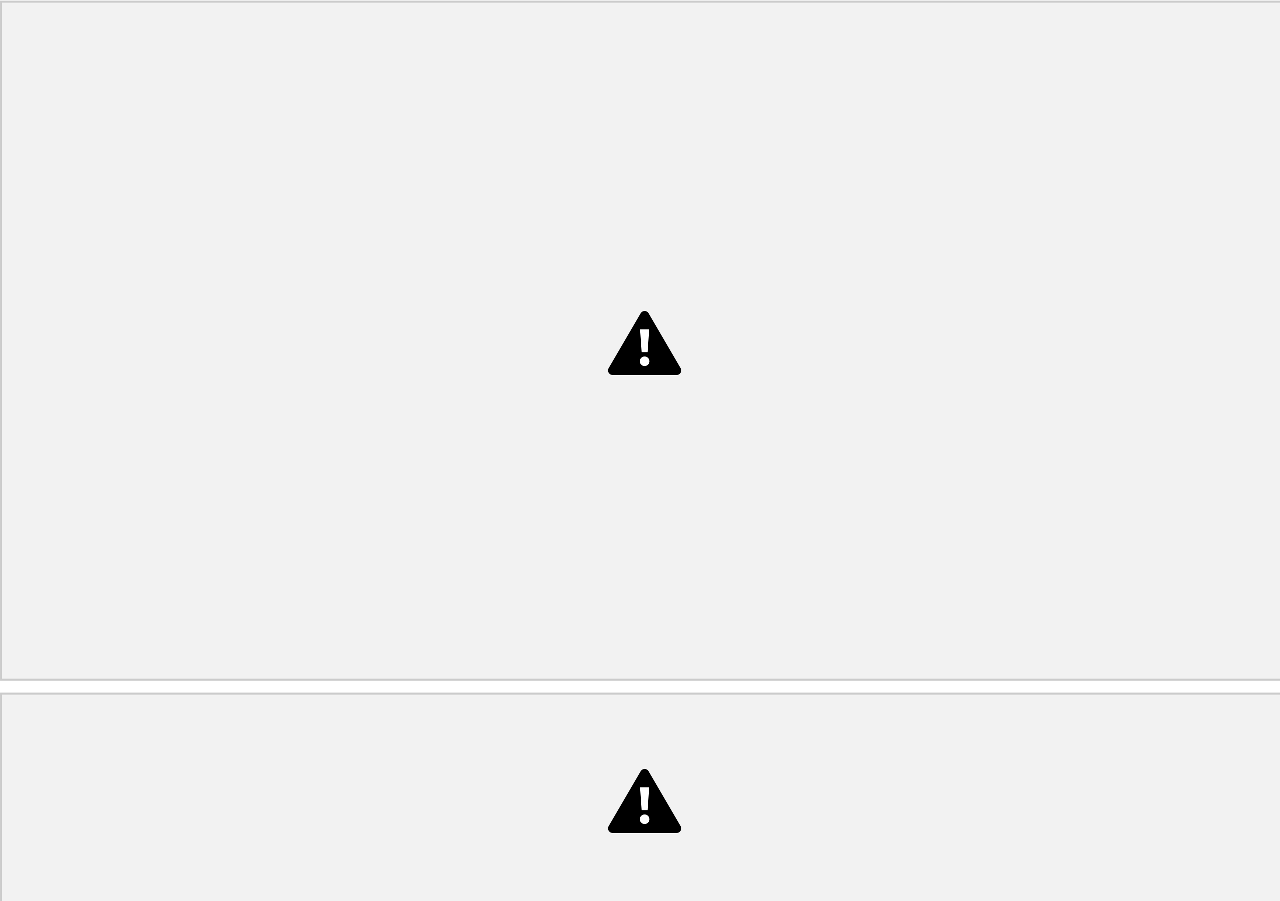


Figure 5: Maps of dug wells in Bahía Blanca. Source: (SEGEMAR, 2000)

The values recorded for flows (blue bars) and temperatures (red dots) of the wells surveyed in the document of SEGEMAR can be seen in Figure 6.

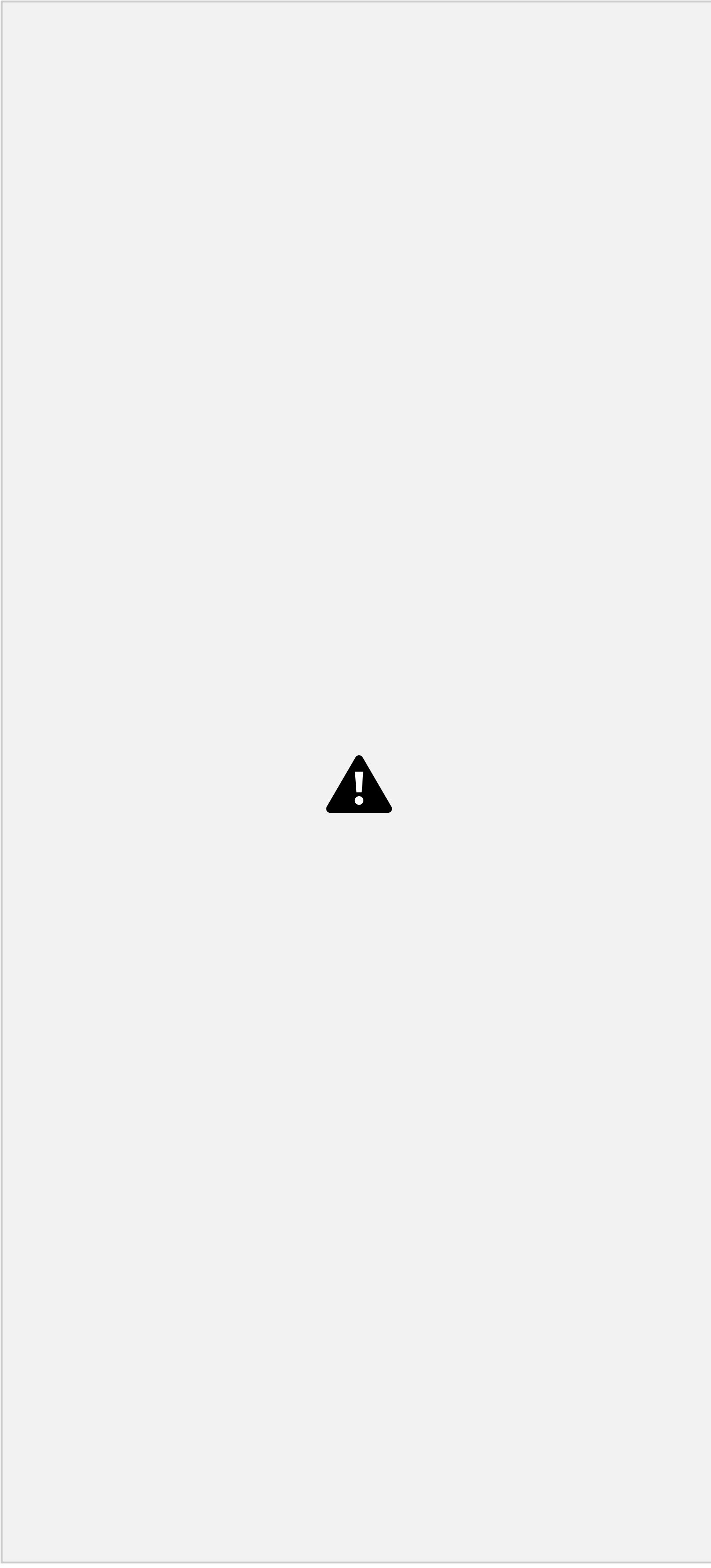


Figure 6: Flow and temperatures of the wells.

As it can be seen, most wells have temperatures ranging from 55 [°C] to 70 [°C] and only three of them present higher temperatures above 70 [°C]. Moreover, only half of the wells have registered information about the flow. In addition, most of them presented a flow below 100 [m^3/h], six wells presented a flow between 100 [m^3/h] and 200 [m^3/h] and only three wells presented more than 200 [m^3/h].

Although the document of SEGEMAR is from the year 2000, the information obtained was beneficial for this work. Additionally, a more recent document was published by the National Institute of Water (INA). In that document, it is reported that wells are still being used, but some have been blocked and closed by local authorities decades ago. Moreover, groundwater quality was assessed, and the results affirm that it is natural, with high properties, which makes it a valuable resource in this urban area. (Ing. Casado, MSc. Lopolito, Lic. Valdes, Lic. Humai, & Téc. Calabro, 2018)

Additionally, by talking with local authorities, it was said that there might exist private wells which were not reported to the Local Water Authority, which presents a further complication when obtaining an exact number of existing wells in the region.

Nevertheless, personnel from the local National University of the South (UNS) are working on doctorate projects, and they have been studying SHP exploitation for many years.

Regarding the industrial of water, the possible utilisation of the SHP is convenient because many of these industries need a considerable amount of water. Currently, the industrial water supply consists of raw water provided by Paso de Piedras Dam, which, due to its weather dependence, after dry seasons, could be scarce.

On the other hand, it would be highly convenient to take advantage of the temperature of the water. However, some companies have tried to drill new wells around Ing. White, but the results were not as promissory as expected.

In 2018 a project was published by José Casado about the heat use from the aquifer. The document analyses the possible heat utilisation to be provided into the main covered swimming pool of the Naval Base of Marine Infantry Baterías. The field results considered it feasible to use the resource to heat the swimming pool with the existing water well. (Ing. Casado, Lopolito, & Coriale, Energía Geotérmica: Aprovechamiento De Pozos Profundos Surgentes, 2018)

Moreover, in Bahía Blanca, there is a nursery garden in which the geothermal water is used to irrigate the water and provide heat to the greenhouse which is shown in Figure 7.

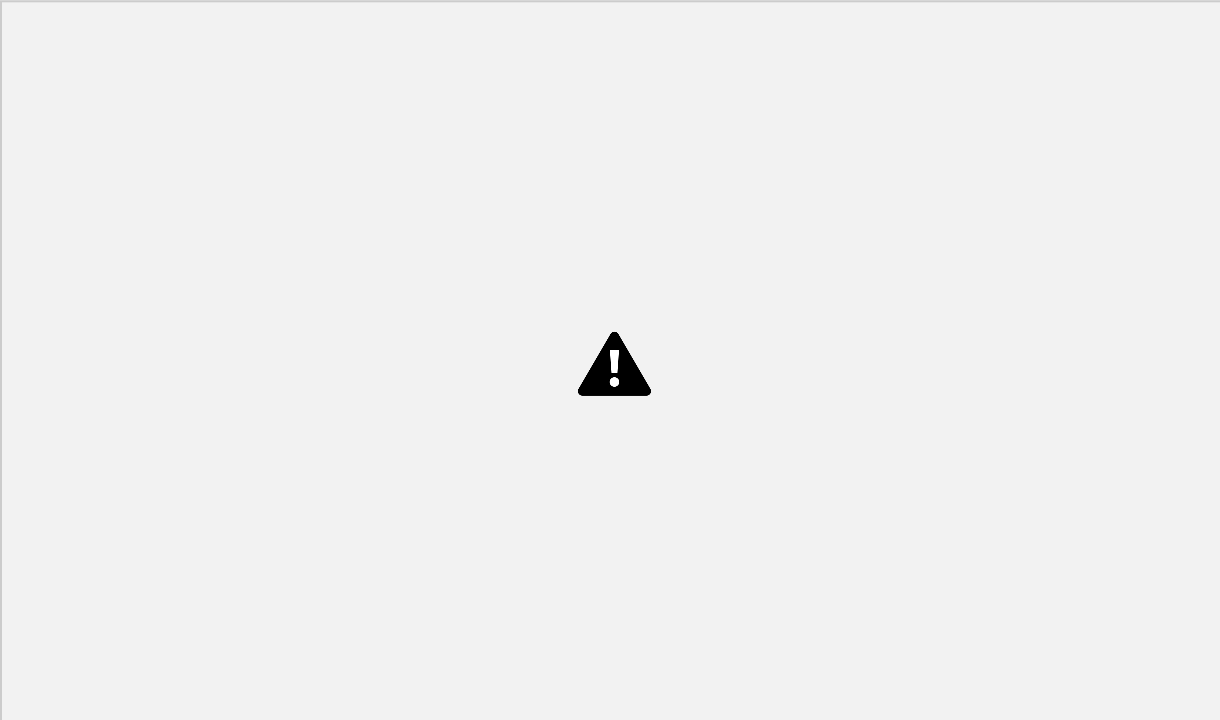


Figure 7: Nursery Garden using heat from geothermal water. Source: (Televisión Pública, 2011)

Another case where the geothermal water is used is in a jail located in Bahía Blanca. The geothermal water is used to heat fish tanks in the building, where tropical fish are bred. This activity forms part of a group of tasks performed by the inmates to learn about this particular job. The fish tanks are shown in Figure 8.

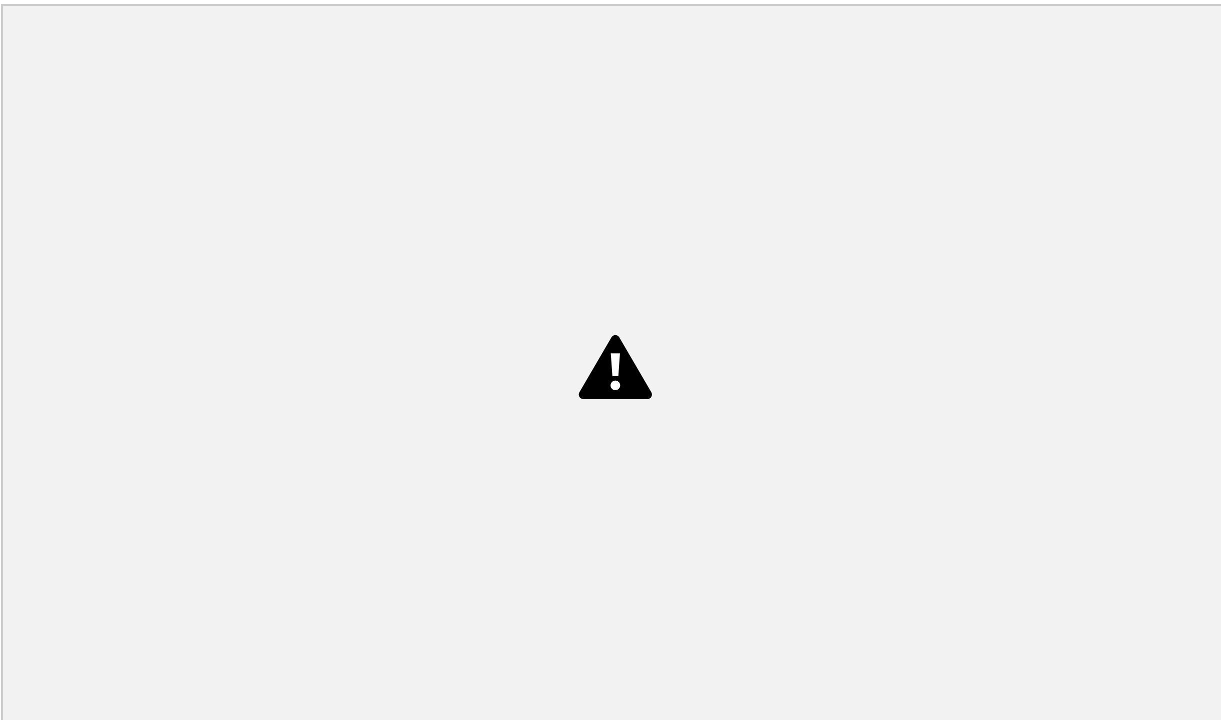


Figure 8: Geothermal heat use in a jail of Bahía Blanca. Source: (Televisión Pública, 2011)

In addition to the previous examples, there also exists other current kind of use without heat utilization, which serves as freshwater provision. People retrieve drinking water from available wells, which are easily accessible across the city. Therefore, the local company, ABSA, periodically performs quality tests to control the water's chemical properties and ensure its drinkability. For security reasons, regulations posts have been embedded inland.

As the water comes out directly from the SHP's aquifer, it has a high temperature, making it unpleasant for consumption. For this reason, people collect water in jerrycans, take them to their houses and let them cool down during the night.

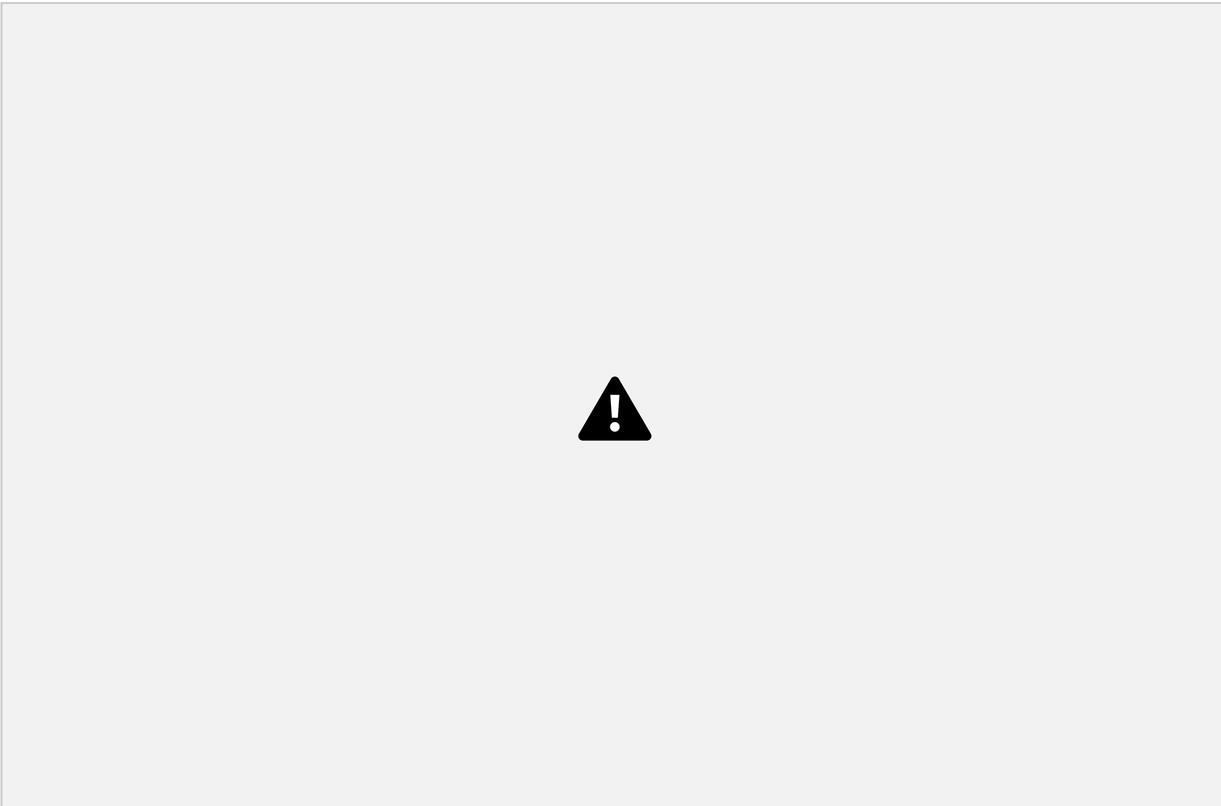


Figure 9: Public geothermal water taps. Source: (La Nueva, 2017)

Sometimes, when the potable water provision is affected and limited, the amount of people collecting water increases considerably. In the period 2005 - 2009, a succession of dry years was recorded in the region, with an average rainfall of 495 [mm], well below the annual modulus (674 [mm]; period 1960 - 2009). This fact led to a notable decrease in the Paso de las Piedras Dam; from a maximum dammed volume of 328 [hm^3], the values were below 70 [hm^3].

This situation generated what the press called a "water crisis". Thus, in 2009, the provision of water to the industry and even to the inhabitants of Bahía Blanca was sharply limited, causing people to resort to SHP wells, where endless queues were formed (La Nueva, 2016)

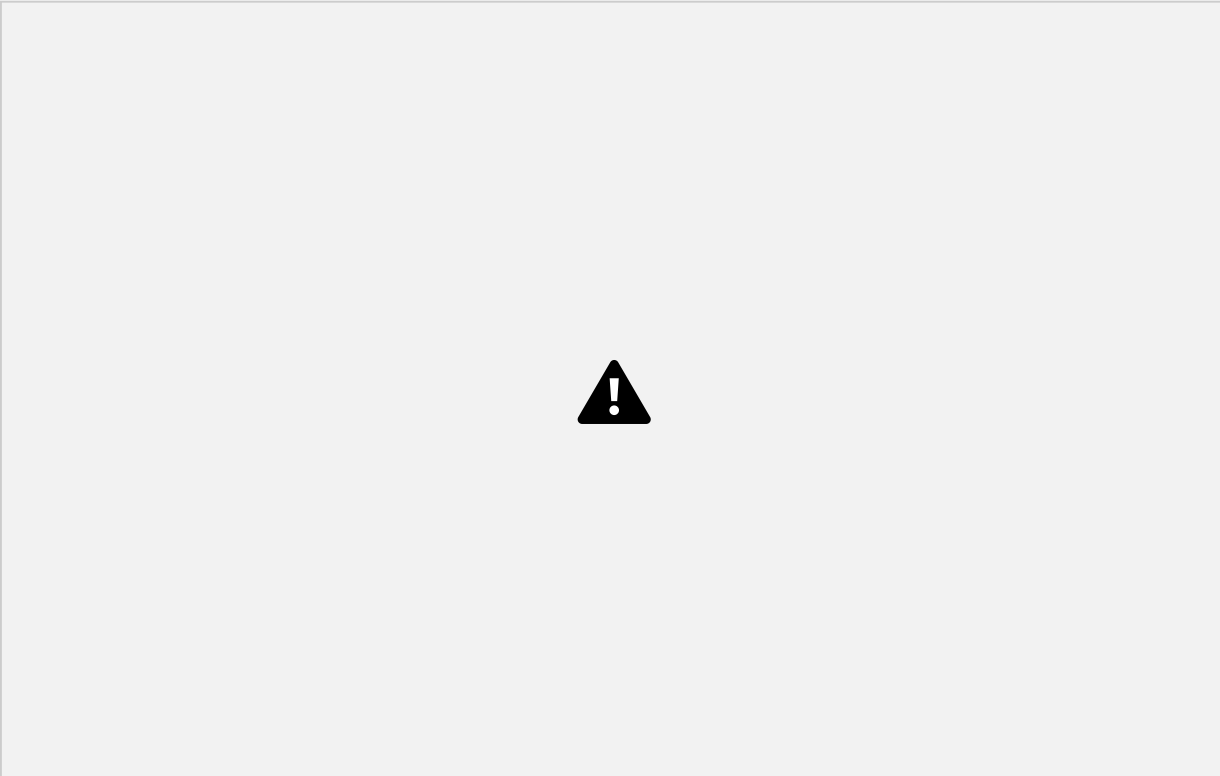


Figure 10: People waiting for filling water bins. Source: (La Nueva, 2017)

Due to the previously described issues, it is indispensable and essential to consider the resource in Bahía Blanca as a valuable resource that all the inhabitants of Bahía Blanca have appreciated for many years. In this way, if it is considered to develop a new project that considers the resource's sensibility for the inhabitants and people of Bahía Blanca.

In this way, due to the deficit of fresh water in Bahía Blanca, the idea of taking advantage just of the heat content of the geothermal water would be a misuse of this valued resource. Then, in Bahía Blanca, the geothermal projects should consider utilize the heat and the potable water.

1.5.6 Industrial sector of the surrounding area

The city has a large petrochemical park installed in the port area, where fuel, plastics and fertilizers are produced. At the same time, there is an excellent development of the network of companies that provide services and technological solutions to the rest of the industry.

Currently, Bahía Blanca is one of 9 petrochemical parks from Argentina, and it is the fifth-largest petrochemical industry park in South America in production capacity.

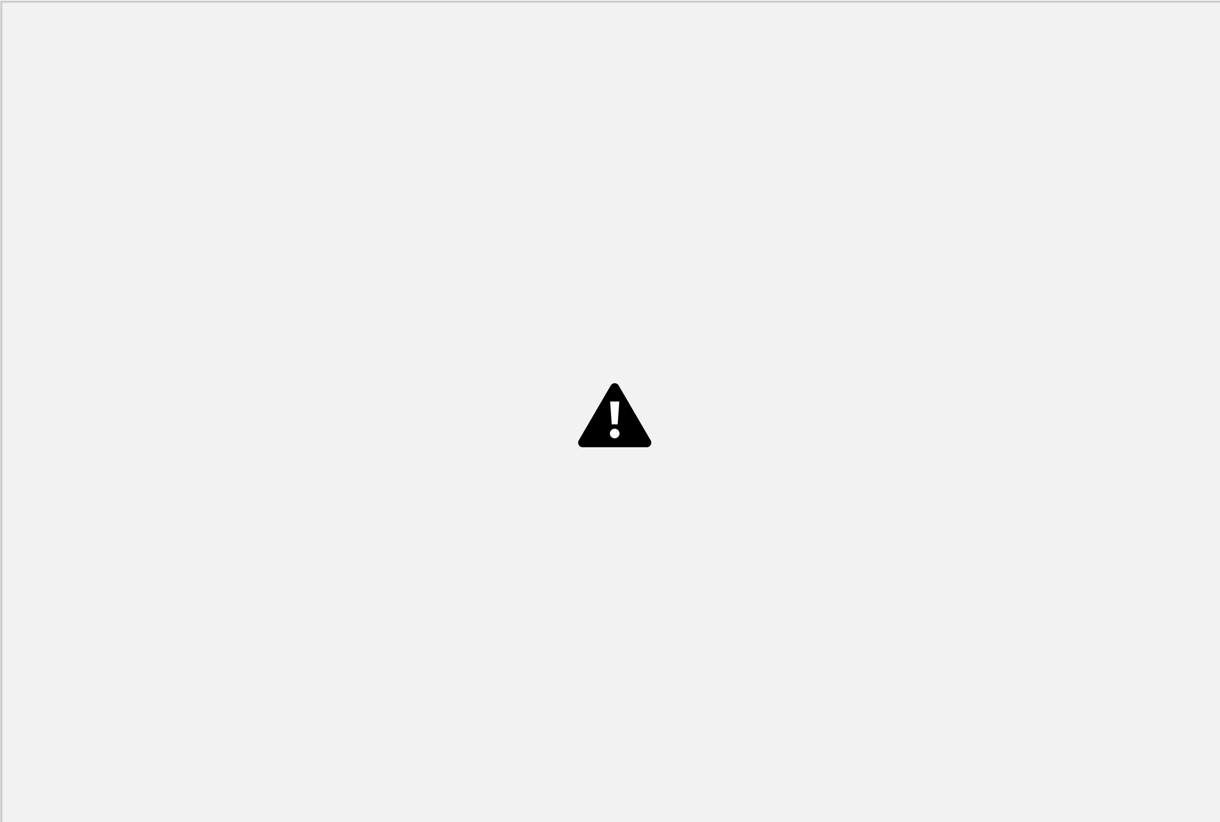


Figure 11: Port area. Source: (Consorcio de Gestión del Puerto de Bahía Blanca, n.d.)

According to studies by the Regional Centre for Economic Studies of Bahía Blanca Argentina (CREEBBA), the contribution of petrochemicals to the gross product of Bahía Blanca reaches up to 25%.

This industrial park concentrates 65% of the petrochemical production nationwide and 56% of the Argentine exports of the sector, according to the same 2015 CREEBBA study.

It is located in the Port of Ingeniero White. It is the only deep-water port in the country, with up to 50 feet of draft, which allows the traffic of large vessels for the loading and unloading of petrochemical, flammable and cereal products, among other cargoes, with a volume of traffic close to the 14 million tons annually. Likewise, the land transport infrastructure network allows the port to be connected to a broad region of influence.

The localization of the petrochemical complex responds to the competitive advantages that this area has:

- The presence of a port with deep waters,
- Availability of qualified labour as a consequence of the existence of university, • The possibility of accessing gas (one of the primary raw materials in the petrochemical industry) given the presence of the union of 3 gas pipelines,

- Extensive road and rail networks and nearby salt mines allow the production of sodium chloride (an essential raw material).

The leading companies that make up the Petrochemical Pole are:

- Company Mega SA,
- Unipar Indupa,
- Profertil SA and
- Dow Chemical.

Valuing each company's products, based on the international prices obtained through INDEC, an approximate global Gross Value of Production (GVP) of the Bahia petrochemical sector for the year 2017 was estimated at 3.1 billion US dollars.

Regarding the highest VBP, Dow leads the ranking, followed by Unipar Indupa, while Profertil and MEGA are in the third and fourth corresponding places, respectively.

The future of the Bahia Petrochemical Park will be closely related to the development of Vaca Muerta[1] since the possibility of increasing gas reserves would allow the expansion of the companies' production.

Different investments have already been made, and projects are under development, such as the 700-kilometre-long railway route that would link Añelo with Bahía Blanca to connect the largest unconventional hydrocarbon reservoir in the country with the local port area.

In addition, the train could be used to transport fruits from the Río Negro valley to the ports for export, generating positive externalities for the rest of the local and regional economic activity. (La Nueva, 2018)

[1] The Vaca Muerta Formation, commonly known as Vaca Muerta is a geologic formation located in the Neuquén Basin in northern Patagonia, Argentina. It is known as the host rock for major deposits of shale oil and shale gas in the country.

1.6 Technologies for geothermal heat utilization

At present, geothermal plants are divided into two large categories: the generation of electrical energy and the direct use of heat. The first is constituted by the so-called geothermal plants — facilities that produce electricity from thermal fluids — either in steam, water, or a mixture of both at a very high temperature.

Commonly, geothermal electricity generation is limited to fluids above 150 [°C], but lower temperatures can also be employed.

1.6.1 Direct Heat

The direct use of heat consists of the immediate use of thermal fluids, taking advantage of the heat that they transport. The primary forms of direct use include:

• swimming, bathing and balneology (therapeutic use),
• heating and cooling including municipal heating,
• agriculture (mainly heating of greenhouses and animal farms),
• aquaculture (heating of pools for fish and crustaceans),
• processes industrial (small, medium and large scale), and so on.

Most of the applications use fluids between 50 [ºC] and 150 [ºC], and in general, the reservoir can be exploited by conventional water well drilling equipment. Traditionally, the direct use of geothermal energy has been conducted on a small scale. However, the efficiency of new technologies has meant that more recent developments involve large-scale projects, such as municipal heating (Iceland and France), greenhouse complexes (Hungary and Russia) or major industrial uses (New Zealand and the USA). (SEGEMAR, 2000)

1.6.2 Heat Pumps

Including a Heat Pump in a project of geothermal water would enable the combination of the heating and cooling capacities. This inclusion increases the efficiency of the geothermal well utilization.

Based of energy transfer, heat pumps use the refrigeration cycle to generate useful heat transfer by means of electricity. The refrigeration cycle consists of the following four steps:

- The refrigerant gas is compressed and superheated in a compressor.
- The gas goes thought the condenser to release the heat and therefore the gas is condensed.
- After the expansion valve, a mixture of liquid and gas at lower pressure and lower temperature is obtained.
- The cold liquid-gas mixture goes to the evaporator for taking heat before returning to the compressor to start the cycle again.

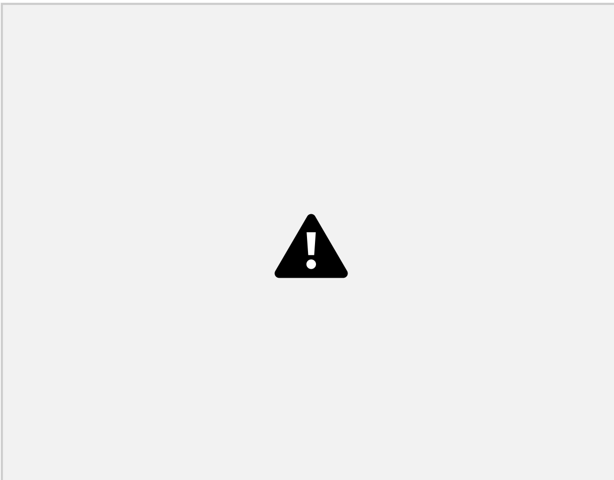


Figure 12: Heat pump stages. Source: (Lun & Tung, 2020)

Additionally, to generate air cooling and air heating, heat pumps can provide chilled water. The capacity of reaching specific outlet water temperature is significantly improved in the las years. In the early twenty-first century, the maximum temperature of heat pump was around 45 [°C]. Due to technology enhancement, most of the heat pumps nowadays can obtain hot water up to 60 [°C].

Moreover, with advanced heat pump technologies, high performance heat pump can produce hot water up to 90 [°C] by using environmental refrigerant (e.g., R134a). High temperature heat pump can potentially replace steam boiler and electric heater with much higher coefficient of performance (COP). With the application of high temperature heat pump, the acceleration in energy efficiency can be achieved (Lun & Tung, 2020).

The possibilities of using the existing resources of Bahía Blanca will be analysed in this paper.

2 Methodology

This section will present the selected company which was chosen for the analysis. The operative system will be described with all the boundary conditions provided by the company. Next, the comparison three cases will be presented, which will be used to compare the possible alternatives. Then, all the made assumptions and taken considerations will be reported. Finally, the equations used in the Microsoft Excel files are shown and explained before going further into the obtained results.

2.1 Assessment of industrial requirement of geothermal heat

For this study, companies from different industrial sectors were analysed, and many local contacts were involved in finding appropriate users for such a project with geothermal water. After speaking with several local people from diverse institutions and organisations, a global food company case, which is currently utilising geothermal water, was chosen.

This case was selected due to many reasons. First of all, the size and relevance for the local industry were attractive. In addition, they were evaluation a project related to finding new water sources. Additionally, this company has high standards for the environmental impact, and thus such a project could be taken into consideration because of its benefits with the CO_2 emission reduction. Moreover, in their processes, the required heat would need a relatively low temperature (just 50 to 60 [ºC]) compared to other cases where a higher temperature would be required. Finally, they also need a cooling capacity to cool the geothermal water down, which would be advantageous for including a heat pump.

The main activity of this company is malt production. In these processes, water is one of the most critical supplies. The production comprises three main steps: steeping, germination and kilning.

Figure 13: Malt production steps

2 Methodology

First, the barley is subjected to different phases of steeping in water and aeration for two days. Then, pricked barley is placed on trays to promote germination for 4 to 5 days. Finally, the green malt is dried by blowing hot air at 58 [°C].

Fresh atmospheric air is heated in two parallel heating chambers. As shown in Figure 14, inside both chambers are different heat exchangers that transfer heat into the flowing air from hot water. The primary heat source of the chamber is a boiler installed close to the chambers where natural gas is used to increase the temperature of heating circulating water which comes into the chamber at a temperature of 127 [°C]. This water releases heat in two heat exchangers in chamber one and one heat exchanger in chamber two.

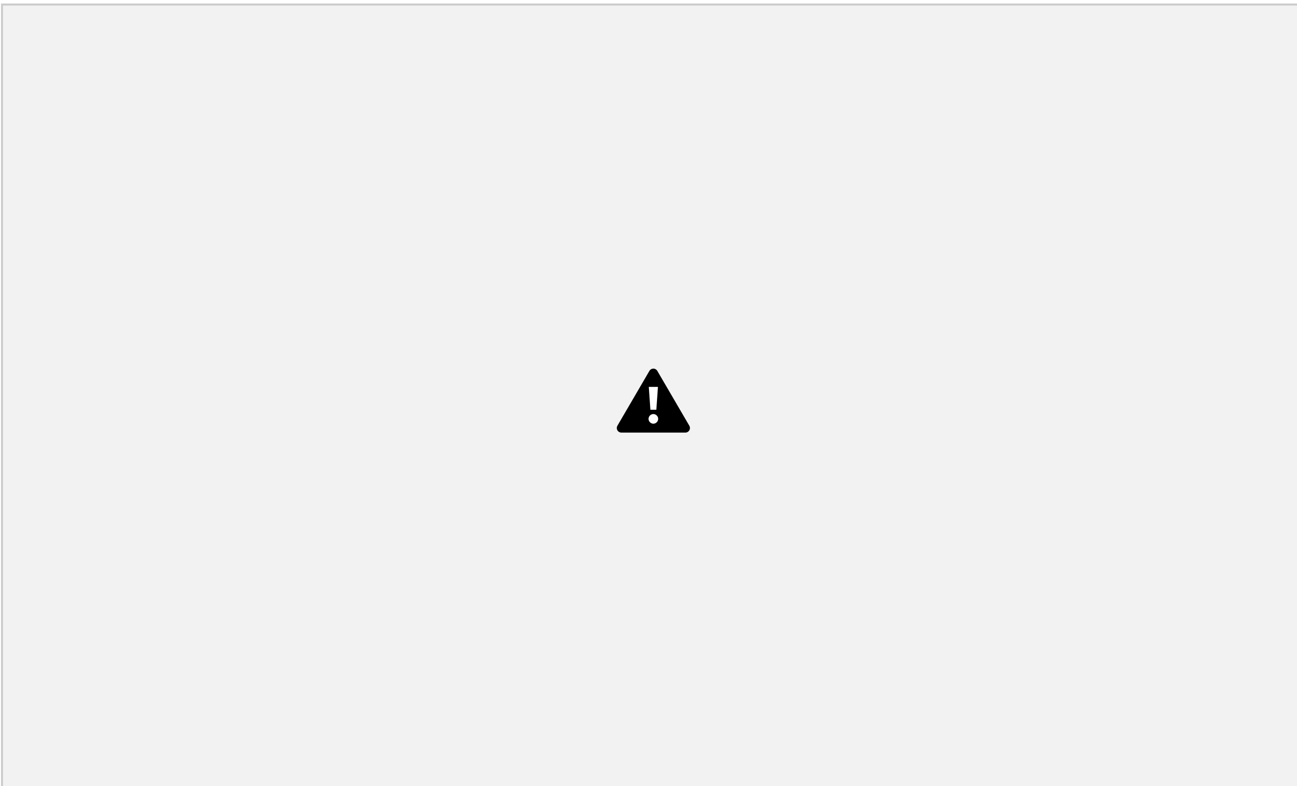


Figure 14: Current plant facilities

In addition to the heating water, a heating circuit containing geothermal water is used in the company plant, and it releases heat in chamber one and chamber two. The geothermal water comes from 845 [m] and 775 [m] depth wells. The well called APW-A1 provides 240 [m^3/day] and the APW-A2 760 [m^3/day]. Both wells fill one tank from which the water is taken. The processes operate at a temperature of 50 [°C] in winter and 56 [ºC] in summer.

After releasing the heat, the geothermal water, which includes superior quality and characteristics, is cooled down and stored for further applications. The water is currently cooled down in an evaporation cooling tower using electricity, and consequently, a temperature of approximately 15 [°C] can be reached.

The company does not own the well with the highest water flow, and the provision of water is regulated by a contract to exploit the well. However, the company is evaluating different alternatives for other external water sources. Considering the required amount of water in their processes, geothermal water should be valued as another standard input for malt production and an essential source of renewable energy.

Therefore, a detailed analysis of the energy balances for different cases will be presented. The alternative of not using the current geothermal water as it nowadays is will be specially analysed. The reason for including the alternative without geothermal water is that the company's engineers considered using another water source without the geothermal heat content.

For example, one considered alternative is to dig water wells at 200 [m] - 300 [m]. These wells contain water that requires a pre-treatment as inverse osmosis. Another alternative is to ask for water from the local provider ABSA. Notably, those alternatives do not include heat content to increase the air temperature, which implies compensation by increasing the burned gas in the boiler.

Subsequently, the current installation will be profoundly analysed, and other more efficient configurations will be proposed. In order to increase the efficiency of the system, the evaluated technologies will be capable of refrigerating the used geothermal water up to a more convenient temperature, and the extracted heat will not be released in the atmosphere but utilised in the processes instead.

2.2 Three cases to compare

As shown in Figure 14, the current installation includes a cooling tower that refrigerates the used geothermal water after coming out from chamber two. Therefore, one possible efficiency improvement would be to include a heat pump technology instead of the cooling tower.

Due to that change, the heat extraction from the geothermal water would play a role because, on the one hand, it would decrease the water temperature. On the other hand, this heat could be introduced into chamber two, and consequently, the heat requirement from the boiler would

decrease, generating gas savings. The heat pump location in the system is shown in Figure 15 for case C.

As the company was evaluating alternative of abandoning the use and exploitation of geothermal water, this document aimed to assess the exploitation of the geothermal well not only as a water source but also as a heat source. Then, the first comparison would be between the current plant concept (Case B) with the alternative of not using geothermal water (Case A). Additionally, the case of using geothermal water with one heat pump to make more efficient the system (Case C) will also be assessed.

Summarizing, the following three cases to be evaluated are stated below and shown in Figure 15: • Case A - Without Geothermal Heat

• Case B - With Geothermal Heat and existing equipment (Cooling Tower)

• Case C - With Geothermal Heat and one Heat Pump

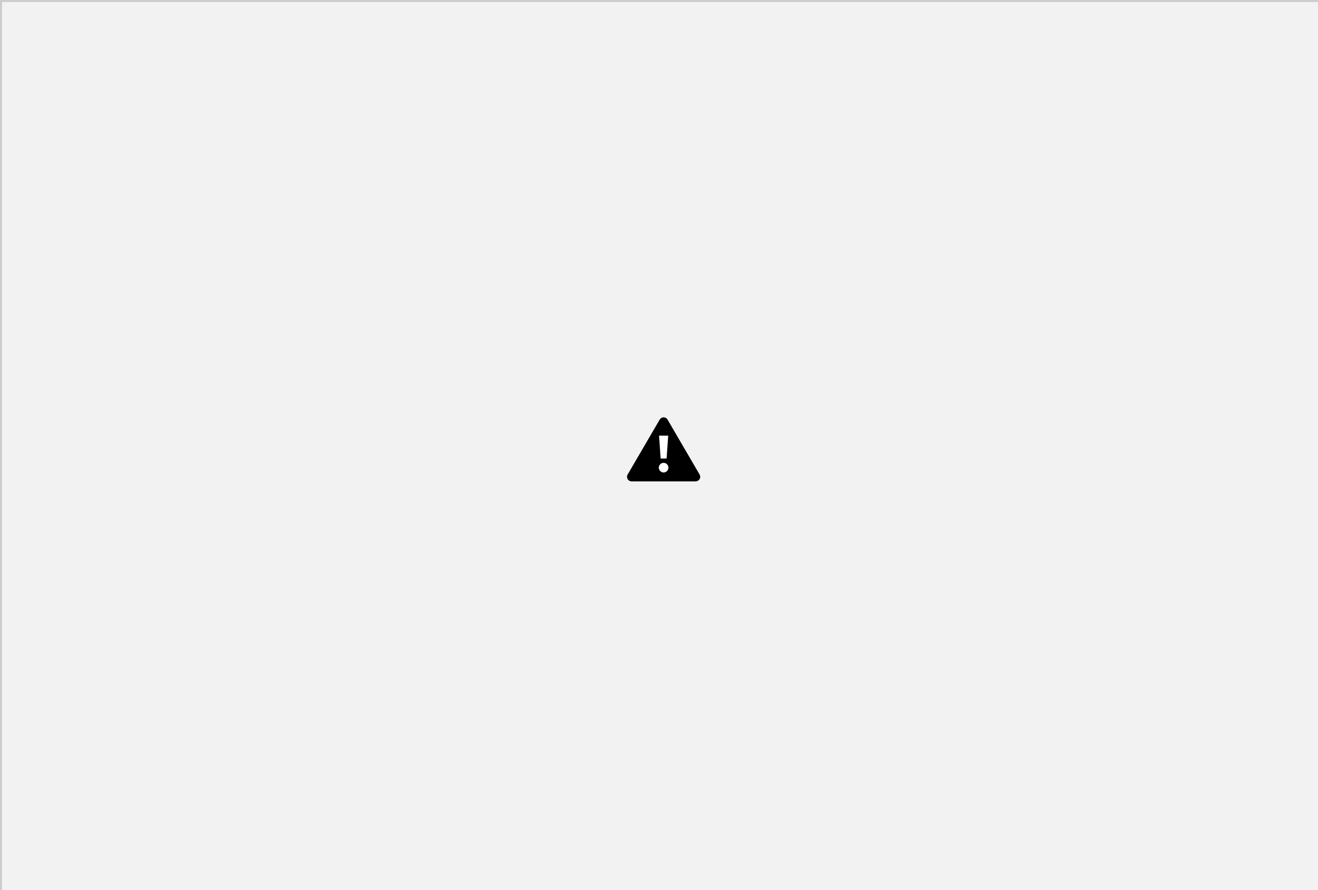


Figure 15: System of three cases

Since fresh atmospheric air is taken from the environment and heated in the chambers as described above, in each season, the inlet temperature of the air will considerably change. Due to that, the air inlet temperature will change every month. Then, in summer, the heat requirement

will be lower, and the geothermal water will come out from chamber two with a higher temperature. In the same way, in months with colder conditions, the results will be the opposite; lower air temperature and thus higher gas requirements. According to the Bahía Blanca climate, it was decided to perform the yearly calculations considering five months with summer conditions and seven months with winter conditions.

In order include into the analysis the electric consumption for the cooling step, the power of the existing cooling tower was asked of the company. Their equipment is composed of two ventilators of 30 [kW] each and two pumps of 15 [kW] each.

2.3 Mass and energy balances

As explained above, for this document, three cases will be compared. However, the first case to be explained is Case B because (shown in Figure 16) it is in operation. After that, Case A, which is similar but without some elements from Case B, will be compared. Then, Case C will introduce the use of a Heat Pump, and everything will be explained.

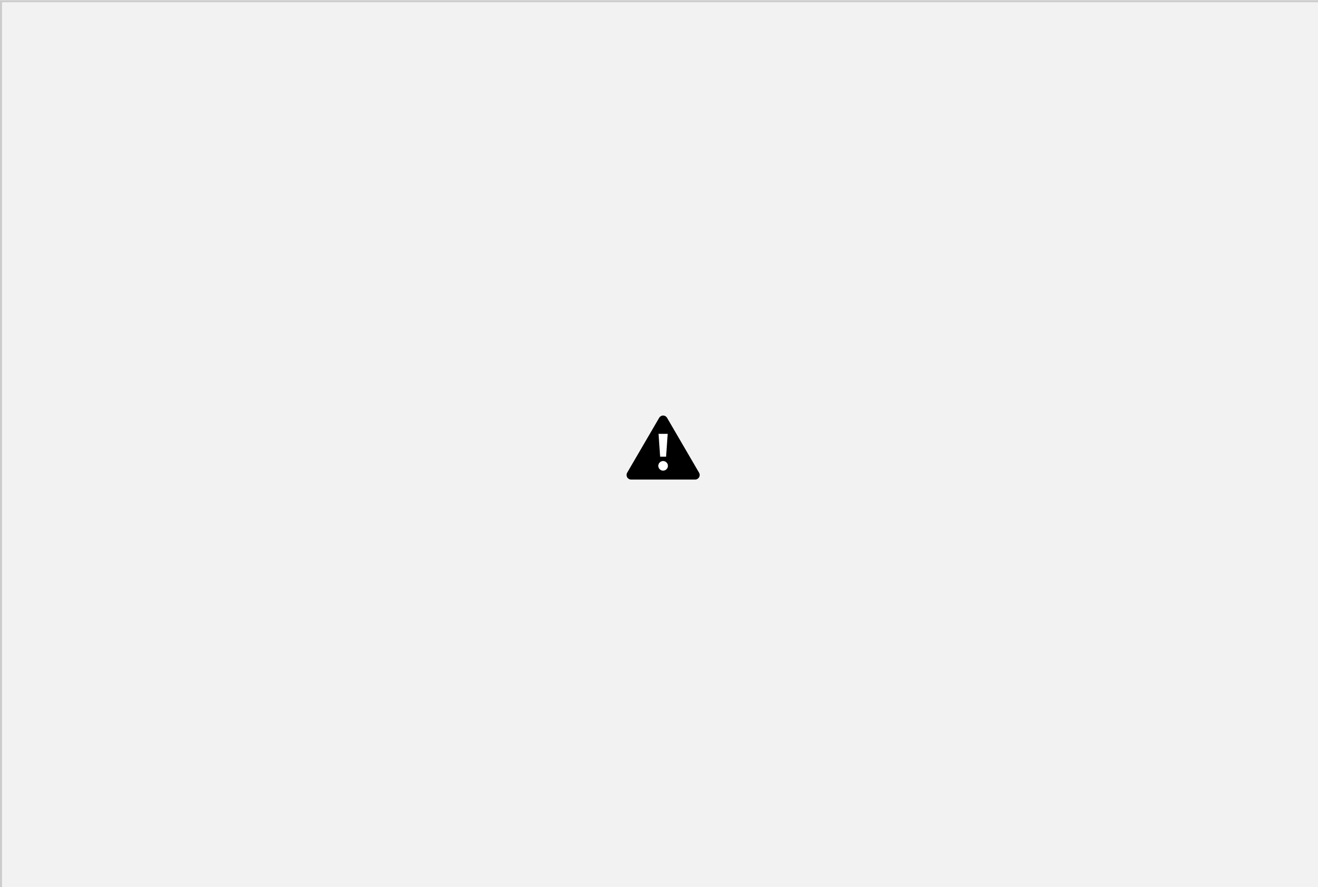


Figure 16: System Case B

For this case, all the operation variables were obtained. These variables were obtained for winter and summer.

As it can be seen in Figure 16, there are two chambers where water releases heat into the airflows. From left to right, there are two fresh air inlets, and one enters chamber one and the other into chamber two. These airflows receive heat from the water circuits and then reach the process temperature required in the Drying and Pre-Drying steps.

On the one hand, in chamber one, there is an air recirculation coming from the Dryer in the first chamber. On the other hand, after pre-drying, the used air is released into the environment.

Regarding the water circuits, we can find two different water circuits. The first is coming from the geothermal wells. As it can be seen, this water exchanges heat with the air in chamber one and also chamber two.

There is also a heated water circuit coming from the boiler to heat the air. This water represents the primary source of heat for the process. In this case, there exist three different heat exchangers. The first exchanges heat with the Heated Air Flow A, then the second heat exchange transfers heat with the Heated Air Flow B and finally, the third one heats the last Air Flow C.

2.4 Description for the system determinations.

The program Microsoft Excel was used to calculate the equations of this thesis. First, all the calculations were made by hand in notebooks and then transferred to Excel's files. This program quickly allowed to design of a system diagram and all the equations involved to interact dynamically with the calculations. In the following image, the used system is shown for Case B.

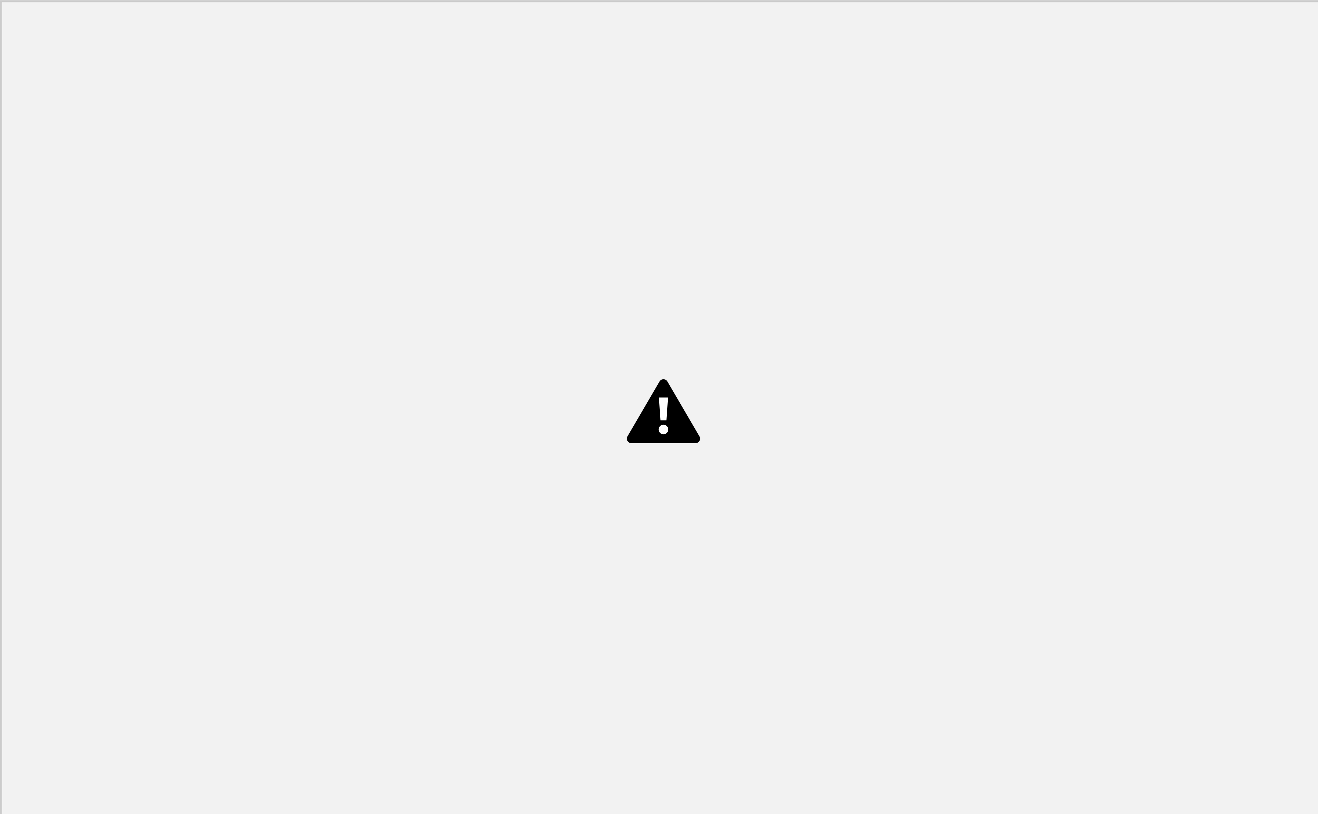


Figure 17: System diagram for Case B with parameters of winter

As shown in Figure 17, the state properties for all streams are included. The company engineers provided some of these parameters, but the rest was obtained employing calculations. The used calculus is presented for each case in the next section. The first case presented was Case B because it is the operative one. Additionally, it is essential to highlight that a letter was attached to each stream to facilitate its description and comprehension.

2.4.1 Case B – With geothermal heat but without Heat Pumps

Mass Balances

The Volumetric Flows and Mass Flow are first required to calculate the heat exchanges. The mass balances are straightforwardly obtainable for the two water circuits because they do not have any mass exchange. In the geothermal water stream, the water comes from the wells, releases heat in both chambers, then is chilled down in the cooling towers and stored in water tanks for further use in the industrial processes. The water circuit coming from the boiler is a closed circuit that serves as a heat source for giving the heat transfer rates $\dot{Q}_3$, $\dot{Q}_4$ and $\dot{Q}_5$ in both chambers.

2 Methodology

The boundaries conditions provided by the company for this thesis were:

Geothermal Water			
	Winter	**Summer**	
Volumetric Flow	**50**	**50**	**[m^3/h]**
Inlet Temp	**50**	**56**	**[°C]**
Middle Temp	**27**	**34**	**[°C]**
Outlet Temp	**20**	**28**	**[°C]**
Required Chilled Temp	**15**	**15**	**[°C]**

Table 1: Geothermal Water operation parameters

Then, for the Boiler's Water circuit, the volumetric flow was an operation parameter and the boiler's outlet and inlet temperatures.

Boiler's Water			
	Winter	**Summer**	
Volumetric Flow	**300**	**300**	**[m^3/h]**
Outlet Temp	**127**	**127**	**[°C]**
Inlet Temp	**83**	**99**	**[°C]**

Table 2: Boiler's Water operation parameters

For this case, the flow sent to each of the three heat exchangers flow $\dot{Q_3}$, $\dot{Q_4}$ and $\dot{Q_5}$ are transferred were unknown. Consequently, these determinations of heat exchanges are detailed in the following sections.

Finally, for the airflow, the system has two principal balances. The first one takes place in chamber one. In this chamber, Air Flow "A" is introduced and heated by the heat exchanger with $\dot{Q}_{1is}$ mixed with the Air Recirculation "F". Then, part of this air flow is sent to the Dryer in Flow "C", and the rest is sent into the Pre-Dryer in Flow "D". For Flow C, the company provided the ventilator's design value is extracting the air from the chamber one. In this case, after drying, the mass flow is recirculated into chamber one, and therefore, the mass flow of F and C are the same.

$$�� [\frac{����}{h}] = �� [\frac{��^3}{h}] \cdot ��_{��} [����/��^3] \quad (1)$$

Then by using the densities of the airflow at each temperature of the winter operation conditions, through equation 1, the airflow **F_F = 388 350 [m³/h]** was obtained. The company also provided the Volumetric Air Flow "D" and is **F_D = 600 000 [m³/h].**

With the corresponding density and equation (1), the air mass flow = 636000 [kg/h] was obtained. With this value, as in chamber one, there is only one inlet in addition to the recirculation of FF, the fresh air inlet mass flow can be directly obtained as $��_{��}$ **= 636 000 [kg/h].**

All the constants used for the calculation of this section and the following ones are presented in section 8 Appendix.

In the next subsection, all the energy balances are explained.

Energy Balances

1. Calculous of heat transfer rate $\dot{��}_{��}$ [kW]

For obtaining the heat transfer rate $\dot{Q_1}$ released by the geothermal water into chamber one, the amount of water, the temperatures of the process provided by the company, the water density and the water calorific power constant are used in the following energy balance.

$$\dot{��} [����] = ��[��^3/h] \cdot �� [����/��^3] \cdot \frac{1}{3600 [h/��]} \cdot ���� [\frac{����}{���� * ��}] \cdot \Delta ��_{������-����}[��] \quad (2)$$

With this equation, $\dot{��}_{��}$ = **1318 [kW]** in winter and $\dot{��}_{��}$ = **1261 [kW]** in summer were obtained. **2. Calculous of boiler heat transfer rate ��$_{��}$**

Additionally, with equation (3), the boiler's power obtained was ��$_{��}$ = **14 435 [kW]** in winter and ��$_{��}$ = **9209 [kW]** in summer.

3. Temperature of heated fresh air in chamber one

Then, by using the obtained ��$_1$ and ��$_{��}$, the temperature of the air in chamber one after the heat exchange can be calculated by means of using the equation (2) obtaining the value of **T_{air1} = 15.4 [ºC]** in winter and **T_{air1} = 29.1 [ºC]** in summer.

4. Calculation temperature in the plenum in chamber one

Then, as a previous step to be able to calculate the heat exchanges $\dot{Q}_2$ and $\dot{Q}_3$ it is necessary to calculate the temperature of the chamber one plenum. In this chamber, a mix between the Heat Air Flow 1 ��$_{��}$ at T_{air1} is mixed with the recirculation �� $_{��}$. The temperature and the following equation were used:

��$_{������}$ [����] = ��$_{����}$ [����] (3) ��$_{��}$

[���� ��] · ����$_{��}$ [����

���� ∗ ��] · ��$_{��}$[��] + ��$_{��}$ [���� ��] · ����$_{��}$ [����

���� ∗ ��] · ��$_{��}$[��]

(4)

= ��$_{������������ 1}$ [���� ��] · ����$_{������������ 1}$ [����

���� ∗ ��] · ��$_{������������ 1}$[��]

Assuming than the specific heat capacity (CP) for the air flows are not so different in these temperatures' ranges, these values can be simplified. According to the given information T_F = 63 [ºC] in winter and T_F = 68 [ºC] in summer.

Then, considering that ��$_{������������}$ [���� ��] = ��$_{��}$ [���� ��] + ��$_{��}$ [���� ��] which are already known, the value of **$T_{Plenum\ 1}$ = 33.8 [ºC]** in winter and **$T_{Plenum\ 1}$ = 44.1 [ºC]** were obtained.

5. Calculation of ���� and ����

Now with the obtained $T_{Plenum\ 1}$ was possible to calculate the heat exchanges by means of the equation (2). The obtained values are ���� = **5009 [kW]** and ���� = **4714 [kW]** for both heat exchangers in winter conditions and ���� = **3610 [kW]** and ���� = **2495 [kW]** for summer.

6. Calculation of ����

Then, in chamber two, to obtain $\dot{Q}_2$ the equation (2) and the provided information were used. The values of ���� = **401 [kW]** for winter and ���� = **344 [kW]** for summer were obtained.

7. Calculation of temperature in the plenum in chamber two

In this case, for calculating the temperature of the plenum, as there is no other inlet of air, the temperature is heated by the heat exchange with geothermal water. Thus, using the equation (2) the obtained value was **$T_{Plenum\ 2}$ = 12.5 [ºC]** in winter and **$T_{Plenum\ 2}$ = 25.8 [ºC]** in winter.

8. Calculation of ����

Finally, to calculate the last heat transfer rate also the equation 2 was used with the given parameters of the air flow F_E. In this case the obtained values were ���� = **4268 [kW]** in winter and ���� = **2883 [kW]** in summer.

9. Refrigeration calculation for cooling the GT water

As explained above the current facility counts with an evaporation cooling tower which chills the water at approximately 15 [°C] before storage it in tanks. According with the given information, this whole equipment requires **P_{CT} = 90 [kW]**. For months of summer is was assumed that they work 24 hours a day and for winter only the 50% of the time.

10. Calculation of gas requirement in boiler

For obtaining the required amount of gas, the Lower Calorific Value (LCV) of the natural gas **LCV = 34 750 [kJ/Nm^3]** was used. Additionally, considering the obtained heat transfer rate at the boiler ��$_{��}$ = **14 435 [kW]** in winter and ��$_{��}$ = **9209 [kW]** in summer, assuming a Boiler's Efficiency of 80% the **Gas Inlet Case B = 1869 [Nm^3/h]** in winter and **Gas Inlet Case B = 1193 [Nm^3/h]** in summer were calculated.

11. Efficiency N-chambers

Finally, after obtaining all the presented figures a comparison of the heat transfer rate provided by the boiler and the sum of the three rates of heat transfer rates **��$_{��}$, ��$_{��}$** and **��$_{��}$** can be made. This difference is shown in the following Table 3:

	Winter	Summer	
Concept	**Values**		**Units**
��$_3$ + ��$_4$ + ��$_5$	**13991**	**8987**	[kW]
Boiler's heat transfer rate	**14435**	**9209**	[kW]
Difference	**444**	**222**	[kW]
Percentage	**2.7 %**	**2.4 %**	

Table 3: Heat transfer rate comparison

Those presented differences could be attributed to diverse reasons. For instance, it could be due to the assumptions of constant specific heat capacities values used during the previous calculus. By simplification, it was assumed in step number 4 that the CPs for comparable air streams. Moreover, the difference could also be due to heat losses in the chambers and the pipeline. Since it is lower than 5 %, the balances were accepted according to the master thesis scope, and therefore the heat losses were neglected.

In the following section, Case A is analysed.

2.4.2 Case A – Without Geothermal Heat

Conversely to Case B, this case is not operational. However, it was analysed because the company is currently thinking about removing the geothermal water source and changing for another type of freshwater source. Then, in this case, the system would be like in the following figure.

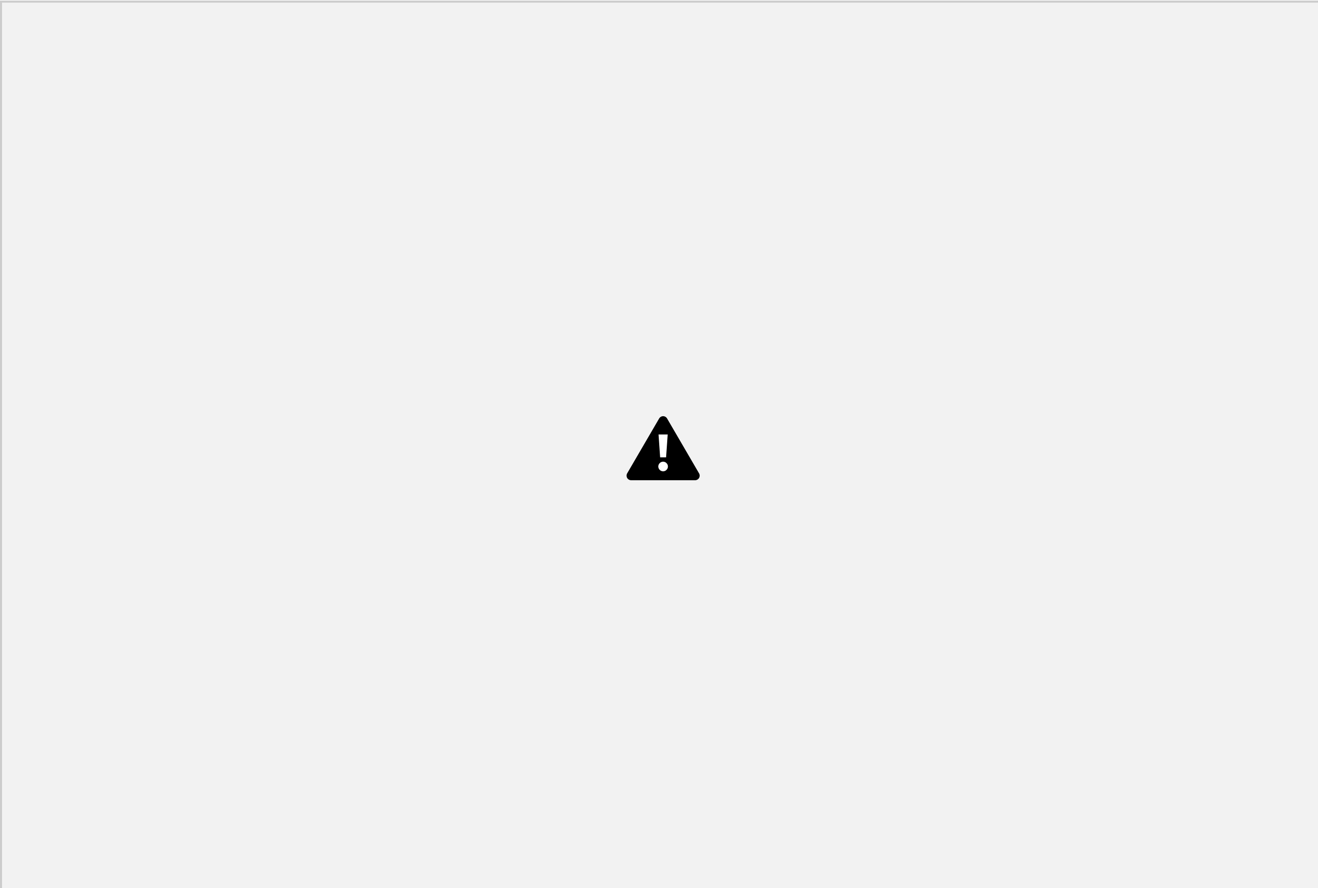


Figure 18: System of the case A

As can be seen, freshwater does not include geothermal heat content. Then, there are no heat exchangers in chamber one or two. Additionally, refrigeration equipment is not necessary anymore.

Therefore, the missing heat sources could just be replaced by the boiler heat in this system. This increment will require an extra amount of burned gas. Next, to calculate the gas increase, the power heat obtained for the former Case B was considered, and then the former geothermal heat exchanges were included in the calculus.

For the explained calculation the following equation was

used: = ���������������� ���������� ��

+ ��1 �������� ��

+ ��2 �������� ��

�������������� �������� �� obtained and for

(5)

= ���� ������ [����] was

In case of winter conditions, a value of �������������� �������� ��

= ���� ������ [����].

summer �������������� �������� ��

Next, considering the assumed efficiency for the boiler at 80% and the same LCV for the gas, the **Gas Inlet Case A = 2092 [Nm^3/h]** for winter and **Gas Inlet Case A = 1415 [Nm^3/h]** for summer were calculated.

Finally, the Microsoft Excel's file document showed the following system for the winter conditions. The case of summer can be found in section 8 Annexes:

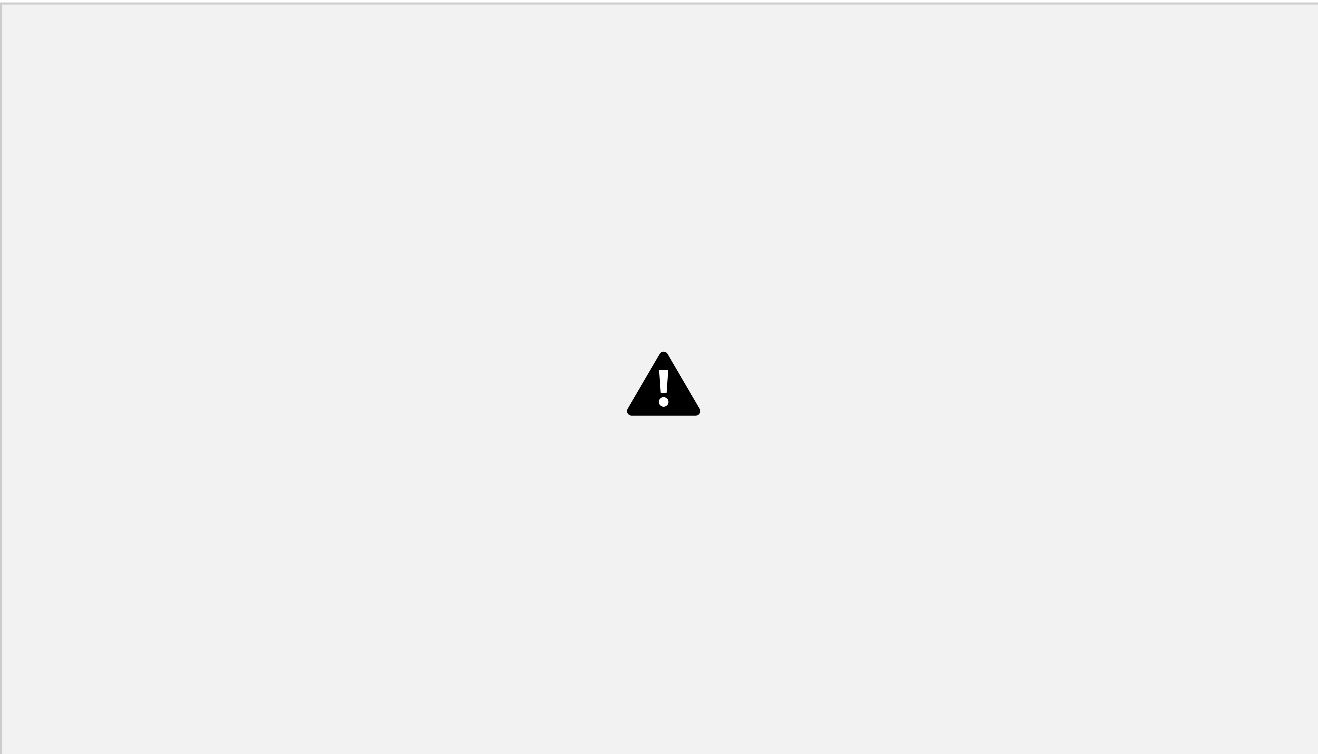


Figure 19: Case A for winter conditions

These cases include heat pumps to make the system more efficient. This equipment requires electricity for its operation, as Case A does. However, in Case C, no cooling towers are necessary. The heat pump chills the water down by extracting heat from it, and this extracted heat is consequently released into chamber two. This heat recovery improves the system's efficiency by decreasing the necessary amount of gas in the boiler. Moreover, not releasing this heat into the environment reduces the CO_2 emission of the heating process. The details are presented in the following sections.

2.5 Heat pump calculations

2.5.1 Case C – With geothermal heat and with one Heat Pump

In the following case, a heat pump was included. This inclusion aimed to increase the system's efficiency and compare this improvement with Cases A and B. Besides this new equipment inclusion, most components are shared with Case B. Consequently, Case C is based on Case B, repeating most of the presented balances above, including just the calculus for the heat pump.

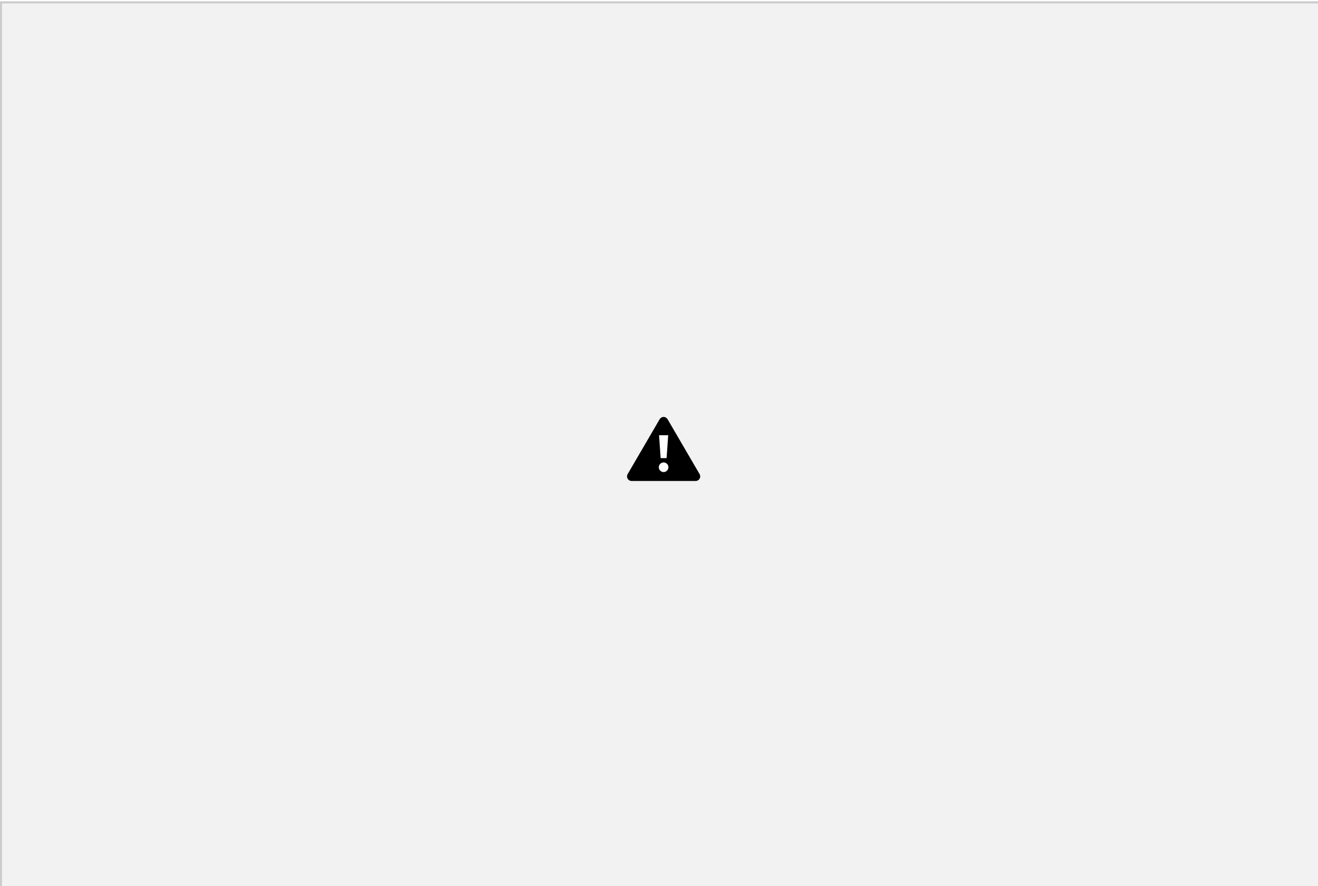


Figure 20: System of case C

As seen in Figure 20, the only difference of Case C between Case B is the inclusion of a new heat transfer rate inlet coming from the heat pump into chamber two. Then, the temperatures inside the chambers were modified, and accordingly, the boiler heat transfer rate requirement. Therefore, the new calculations for this case are presented below.

12. Calculate the ideal Carnot Coefficient of Performance (COP_{Carnot})

To calculate the ideal COP_{Carnot} of the heat pump, it is necessary to consider the values between the Heating and Cooling sides of the Heat Pump. According to the process requirements, the heat pump will operate cooling the geothermal water down from 20 [ºC] till 15 [ºC] in winter and from 28 [ºC] till 15 [ºC] and then releasing the heat into chamber two, which will have a temperature around 15 [ºC] – 20 [ºC] in winter and 25 [ºC] – 30 [ºC] in summer. Then, the manuals of some fabricants of heat pumps were revised. Below is included the catalogue information of the fabricant Ochsner.

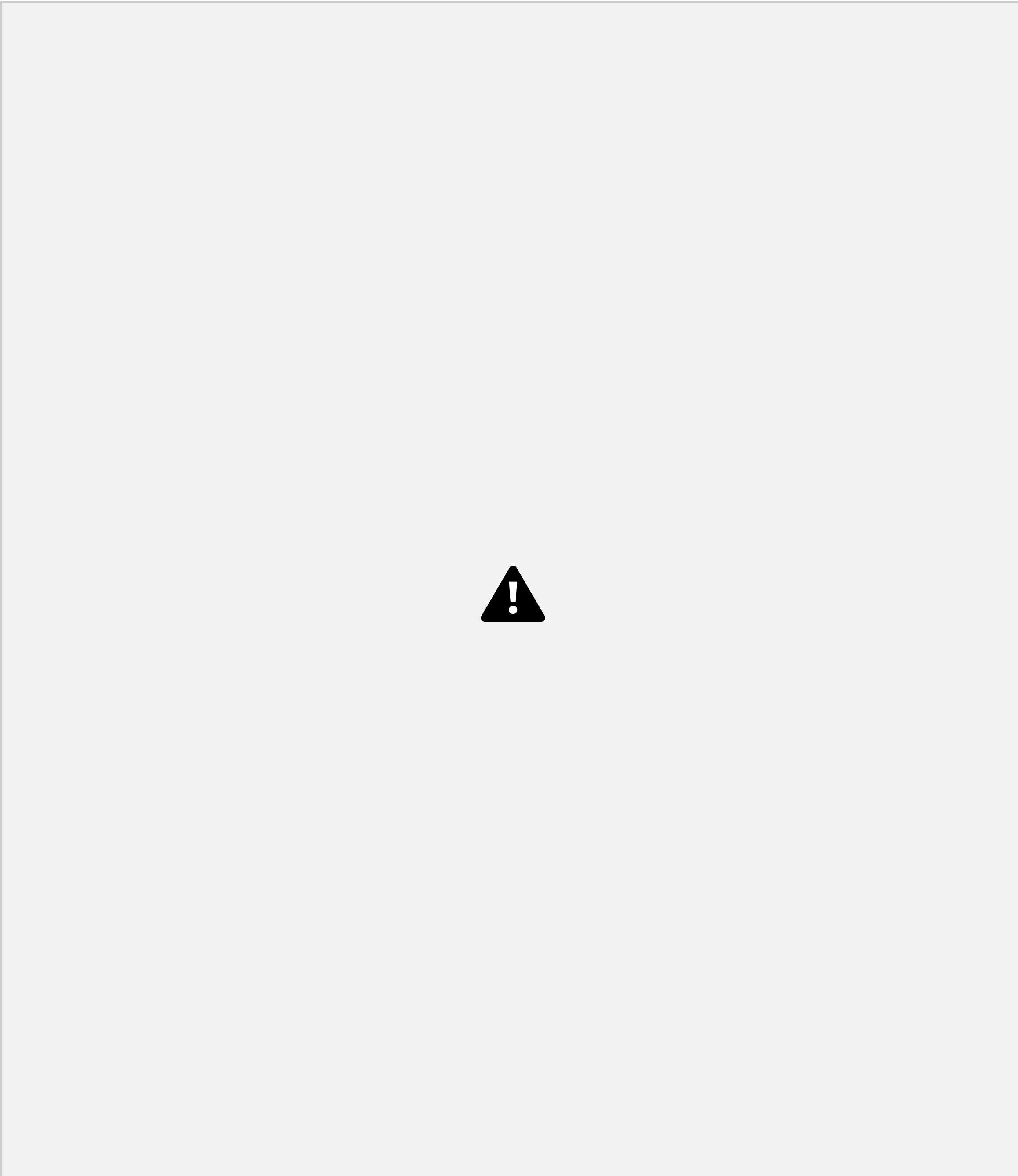


Figure 21: Catalogue of Ochsner Heat Pumps. Source: (Ochsner, n.d.)

Then, considering the offered products and their design's temperatures, the $\mathbf{T_{cooling} = 15}$ **[ºC]** and $\mathbf{T_{heating} = 50}$ **[ºC]** were selected.

Then, with this design parameters, the COP_{Carnot} can be obtained. For calculate this coefficient, the following equation (6) was used.

������������������ =��ℎ������������ �������� [��]
(��ℎ������������ �������� − ��������������� ��������) (6)

Utilizing this equation and the mentioned design parameters, a **COP_{Carnot} = 9.2** was obtained. However, this value represents only a performance for ideal conditions and should be adapted to real processes. To translate this COP to real values, an empirical graph was uses. This graph is presented in Figure 22. On it were represented the relation between the ideal COP_{Carnot} and the real COP for many different heat pump models from five providers. Then, a lineal regression was done in order to obtain a conversion factor. As shown in the figure, the **COP/COP_{carnot} ratio = 55.6%** was obtain (slope of the curve Y = 0.556 X).

All heat pumps

10
Carrier
5
4
3
y = 0,556x
2
COP
9
Engie
1
8
Friotherm
0
0 2 4 6 8 10 12 14 COPc
7
Johnson Controls
6
Ochsner

Figure 22: Ratio between real COP and Carnot COP. Provided by GTN GmbH

Then, using this ratio, a real COP can be estimated at **COP_{real} = 5.1**.

13. Obtaining the Cooling and Heating capacity

For calculating the Cooling Capacity, Heating Capacity and Electrical Power of the Heat Pump, the following equations were used:

[illegible] [kW] = [illegible] [[illegible]] · [illegible] [[illegible] * [illegible]] · ([illegible] − [illegible]) [[illegible]] (7)

[illegible] [kW] = [illegible] ([illegible]) (1 − 1/[illegible])   [illegible] [kW] = [illegible] [kW] (8)

[illegible] [kW] (9)

Using the equations (7), (8) and (9) with the operation parameters of each season, the obtained values were [illegible] = **- 287 [kW]**, [illegible] = **356 [kW]** and [illegible] = **69 [kW]** for winter and [illegible] = **- 756 [kW]**, [illegible] = **927 [kW]** and [illegible] = **181 [kW]** for summer.

14. Calculation of gas requirement in the boiler

Next, with the heating capacity, it can be assumed that this amount of heat transfer rate will be saved in the boiler. Then the heat transfer rate for the case C could be calculated as:

[illegible] [kW] = [illegible] [kW] − [illegible] [kW] (9) [illegible] [kW] = [illegible] [kW] (8)

Afterwards, the obtained requirement of heat from the boiler is [illegible] **= 14 079 [kW]** in winter and [illegible] **= 8282 [kW]** in summer. Therefore, the amount of gas of in winter would be **Gas inlet C = 1823 [Nm^3/h]** and **Gas inlet C = 1073 [Nm^3/h]** in summer.

Finally, the system in Case C for winter with all the obtained parameters is shown below.

Figure 23: Case C for winter conditions

Additionally, the footprint of CO_2 emissions was evaluated and the calculations are presented in the next section.

2.6 CO_2 footprint calculations

15. Specific CO_2 emission for each type of energy used.

For the calculations of the CO_2 emission, the amounts of consumed electricity and gas were taken into account. After that, from the website of the Argentinian government, the following factors of CO_2 emission were used. After that, the values could be compared in terms of Total CO_2 emissions [tCO_2eq /year].

CO_2 Generation Parameters		
CO_2 emissions due to electricity[2]	0.438	[kg CO2 per kWh]
CO_2 emissions due to natural gas[3]	1.951	[kg CO2/Nm3]

Table 4: CO_2 factors for Argentina

16. Equivalences to tangible objects.

To facilitate the interpretation of the obtained figures for the reader, they were also converted to a more tangible concept that could be easier to compare. Then, from the website of Environmental Protection Agency (EPA) of U.S.A., the following conversion factors were used.

CO2 equivalences	
Passenger vehicles per year	
4.63	[tCO_2eq / vehicle / year]
Forest capture of CO_2 for one year	
0.77	[tCO_2eq / acre / year captured annually by one acre of an average US forest]
0.405	[Acre/Hectare]
Tons of waste recycled instead of being disposed into landfills	
2.94	[tCO_2eq / ton of waste recycled instead of being disposed of in landfills]

Table 5: Table for tangible comparisons. Source: (U.S. Environmental Protection Agency, 2021)

[2](Secretaría de Energía de la Nación Argentina, 2006)

[3](Secretaría de Energía de la Nación Argentina, 2019)

2.7 Further methodical considerations

Before analysing the evaluation results, it is necessary to detail other assumptions taken for this work.

As mentioned above, the calculations were made considering five months of "winter" and seven months of "summer" conditions. This consideration was based on the information that the mean temperature of the air in Bahía Blanca was higher than 15 [ºC] during seven months. The mean temperatures are shown in Table 6 obtained from (Climate-data, n.d.).

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mean Temperature [ºC]	24.40	23.00	20.20	16.20	12.40	9.50	8.60	10.30	12.60	15.70	19.30	22.70

Table 6: Mean temperatures of Bahía Blanca

Additionally, all the used constants for water and air used in mass and energy balances are included in the section 8 Appendix.

For comparing the three cases with an economic methodology, all the corresponding expenditures were calculated. Then, the expenditures for gas, water and electricity were obtained, summed and compared for each case. For obtaining the gas expenditures, the company provided a mean value of the yearly cost of gas. The same information was given for the electricity they paid.

In addition, to obtain the yearly expenditures in electricity, it was assumed that the refrigeration system operates for Case A 24 hours a day because the freshwater provided externally should also be chilled down until 15 [ºC]. Then for case B, it was assumed that the cooling towers operate 24 hours a day in summer and 12 hours in winter to reach the desired temperature of 15 [ºC].

It is also important to remark that the investment of a new geothermal well is not included in the analysis. This assumption is because, on the one hand, the company is already using one existing well. On the other hand, the economic evaluation considers the yearly expenditures of each case. Therefore, the future savings due to the Geothermal Heat and Heat Pump implementation could be translated into today's US dollars and compared using the Net Present Value analysis.

2.8 Economic evaluation

The three cases were evaluated and compared using a Net Present Value for the yearly analysis for 15 years. For the Heat Pump investment, the cost of appropriate equipment was consulted to three different companies in Case C. For this evaluation, the heat pump ThermeCO_2 HHR1000 HE of the company ENGIE Refrigeration GmbH was selected as a reference.

This choice was made considering the operational temperatures for the heating and cooling of water. In addition, the heat transfer capacity must be calculated by using the temperatures difference and water flow. The required investment could be estimated at 250 000 €.

No additional investment would be required for Case A and Case B. Meanwhile, for Case C, the investment would be the unit to installed. In addition, the investment in auxiliary equipment (i.e., pipelines, accessories, automation, electrical engineering equipment and others) and engineering services must be included. The cost of auxiliary equipment and engineering services was estimated in terms of equipment costs, representing 10 % and 8 %, respectively.

In addition, the maintenance and repairs during the 15 years of analysis were evaluated. For including them, the yearly amount was estimated at 1.5 % of the heat pump's investment cost for both concepts. The maintenance's cost and repairs were not provided for the refrigeration system in Case B. However, since this equipment was already installed, costs were estimated using 50% of the heat pump's cost and then considering a 1.5 % for maintenance and repairs.

Next, a discount rate of 3 % was considered to translate the future expenditures in terms of today's US dollars. Finally, all the evaluations were made in US dollars, and for converting the expenditures and investment into this currency, the subsequent exchange rates were considered:

Currency Exchange Rates[4]		
Argentinian Pesos	78.64	[USD/ARS]
Euro	1.19	[EUR/USD]

Table 7: Currency exchange rates

Until this section, the presented result was the amount of water, electricity and natural gas for each case. Considering the specific costs shown in Table 8, the yearly expenditure for each case will be calculated. For the obtention of this specific cost of electricity and gas tariff, the yearly mean was calculated with the monthly tariff the company pays. Additionally, for the water cost, the cost was based on the cost that the citizens of Bahía Blanca pay for the freshwater provision. However,

it is vital to consider that for a case of an industrial amount requirement and the water shortage in the region, the price may be differ.

Consumption-tied costs	
Natural gas	0.1027 [USD/Nm3]
Electricity	0.0406 [USD/kWh]
Drinkable water[5]	0.1411 [USD/m3]

Table 8: Specific costs for Natural gas, Electricity and Fresh Water

All the mass, energy and economic evaluation results are presented in the next section.

[4](Cotización-dolar, 2020)

[5](ABSA, 2019)

3 Results

Finally, all the results are presented and explained in this section. In the beginning, the amounts of Gas, Electricity and Water for each of the three cases are assessed. With those values and specific costs for each resource, the yearly amounts will be added to find the yearly expenditures for each case. Then, the hypothetical CO_2 reduction will be presented. At the end, the economic evaluation results for each case will be explained.

3.1 Gas, Electricity, Water and CO_2 results

3.1.1 Gas demand

The yearly demand for gas was estimated for the three cases and compared in the following graph, where the amount is expressed in [N hm^3/ year].

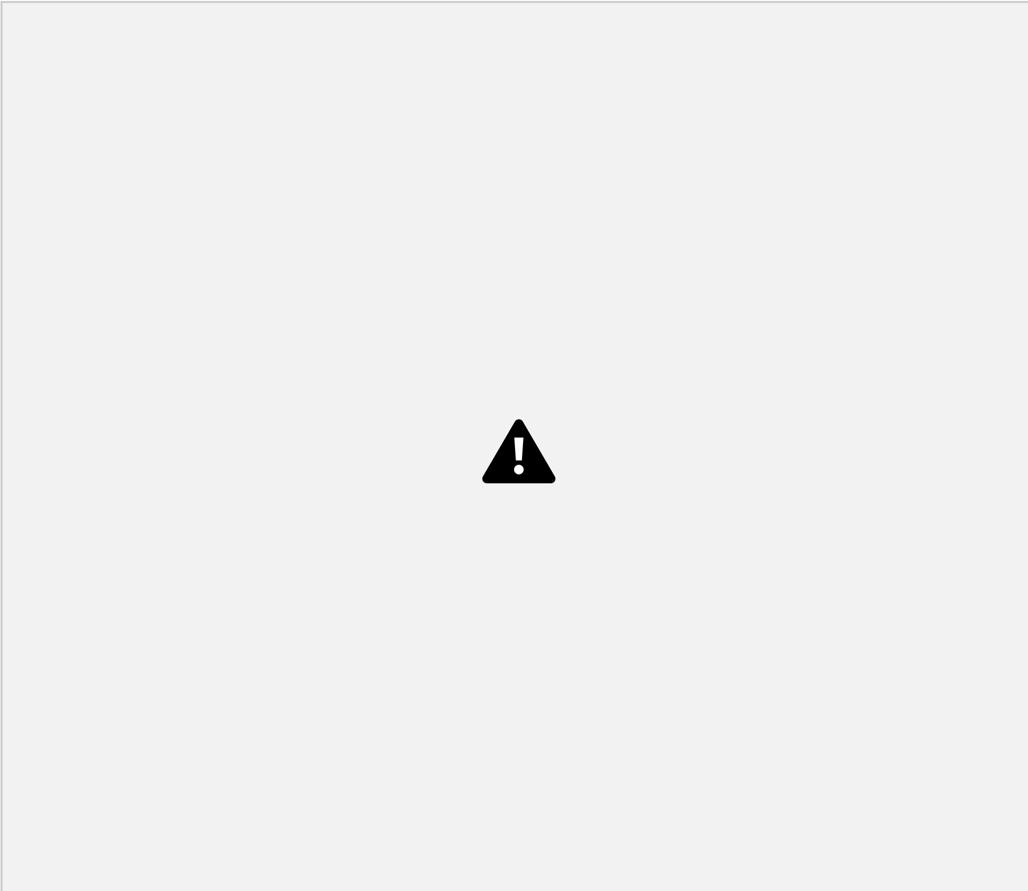


Figure 24: Gas yearly demands

As seen above, Figure 24 states that in case of not using geothermal water, an amount of 14.59 [Nhm^3] of natural gas would be needed every year. Instead, using geothermal heat would

decrease around 13 % of the natural gas requirement. Additionally, the gas savings in the case of including a heat pump is shown. Using geothermal water with one heat pump would decrease the need for gas by approximately 18 %.

3.1.2 Water demand

Regarding the water demand, as explained before, only the case which does not include the geothermal well use would require an external source of freshwater for the industrial processes. This external source would imply an extra yearly cost shown in the following graph.

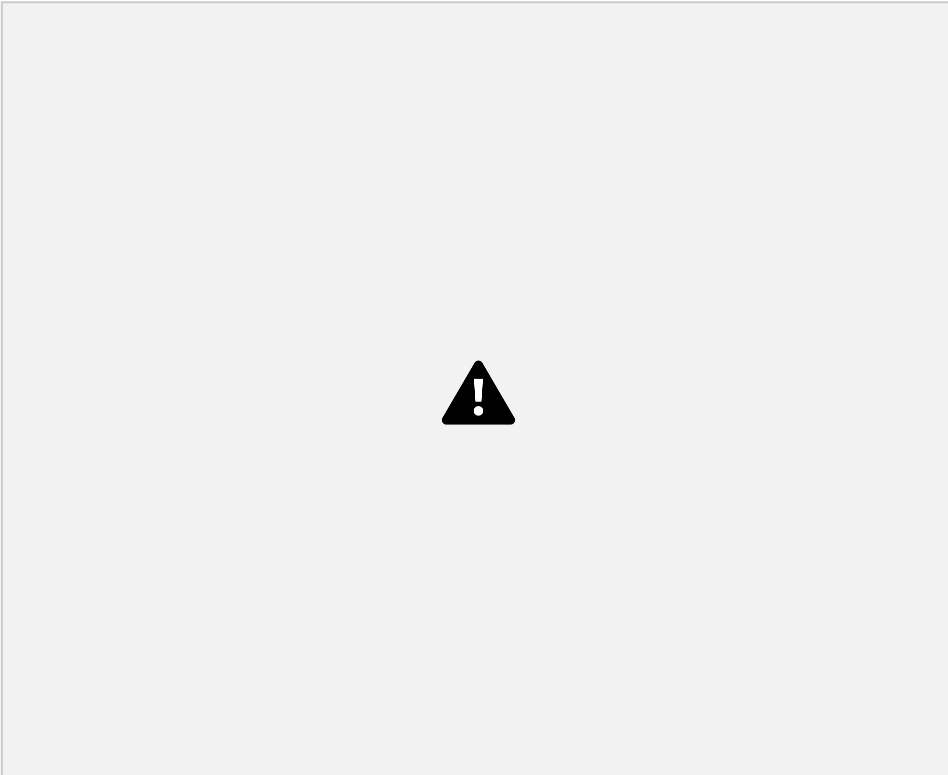


Figure 25: Fresh water extra provision requirement

3.1.3 Electricity demand

Regarding the electricity consumption, the following graph shows the requirements for each year. As detailed before, it was assumed that Case A only requires cooling in summer. In Case B, the electricity was estimated for the existing refrigeration towers, whereas for Case C, the electricity consumption was calculated using the heat pump design parameters.

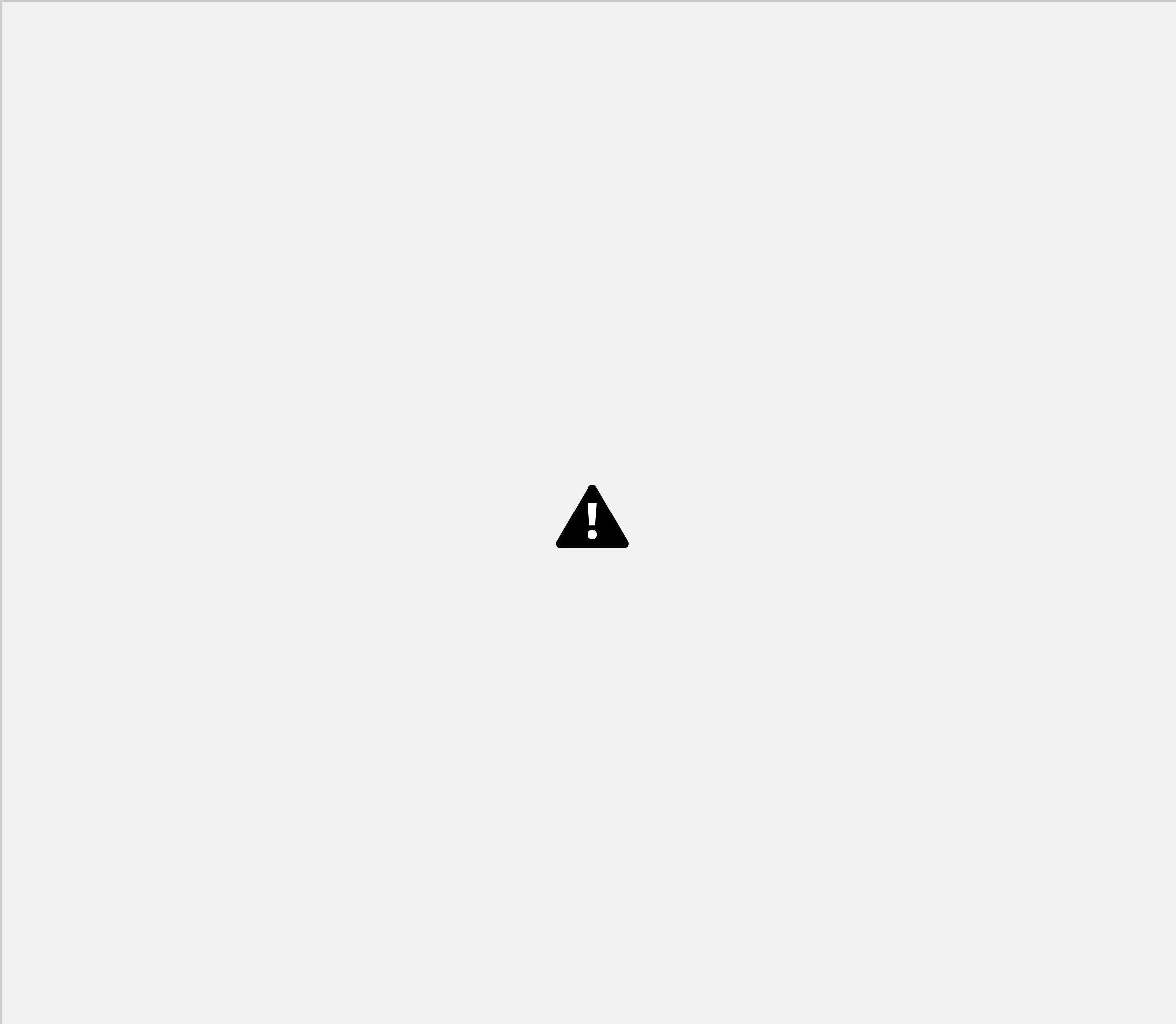


Figure 26: Electricity requirements

As can be seen, using a heat pump increases electricity usage. However, part of this energy will be converted to heat by the heat pump and consequently transferred into chamber two.

3.1.4 Yearly expenditures

Thereupon, considering the mentioned costs, the yearly expenditures for each case are shown below.

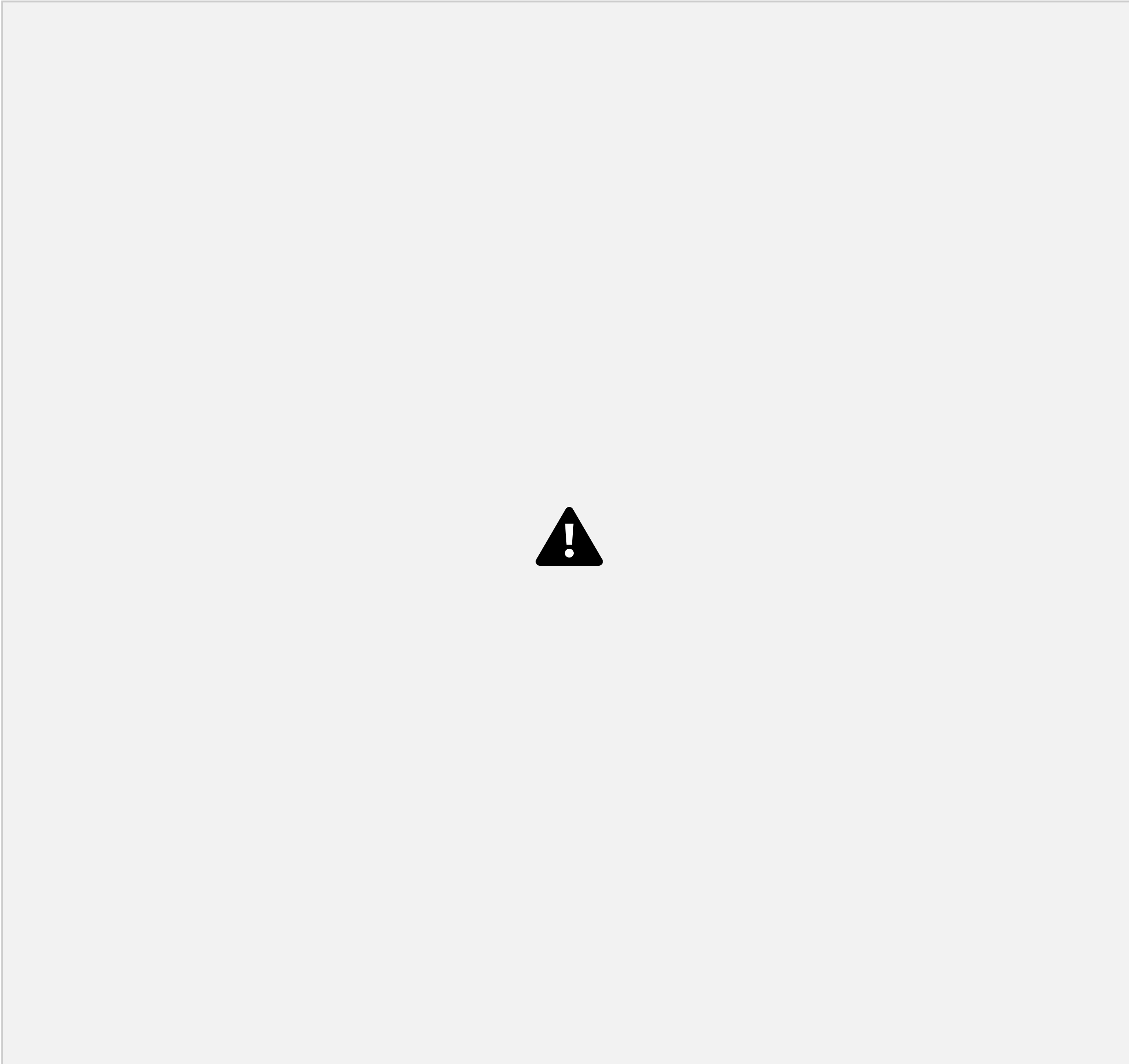


Figure 27: Yearly expenditures for each case

Using geothermal water implies a 15 % savings in the total expenditures compared to not using geothermal water. In the case of one heat pump, the savings would reach up to 19 % in terms of USD per year. Therefore, it can be concluded that the main source for expenditures is the natural gas. The table with the values for the above presented figure is included in Table 9.

3.1.5 CO_2 emissions

This document includes calculating greenhouse gas emissions as something additional to the economic point of view. Subsequently, the obtained figures of the alternatives are shown in Figure 28.

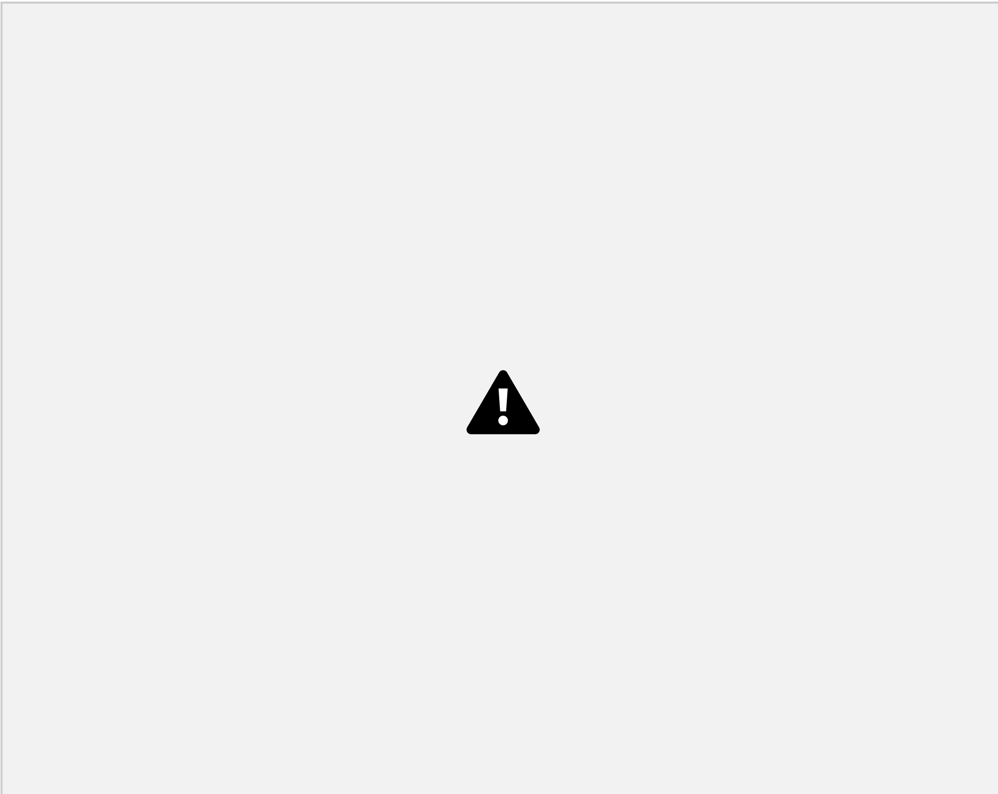


Figure 28: GHE comparison

As can be seen, using geothermal energy produces a decrease of 13 % in equivalent CO_2 emissions. By introducing one heat pump in the system, reduction escalates up to 17 %.

Some equivalences explained in the methodology section facilitate the interpretation of these figures. The resulting equivalences between Case A and Case B are presented in Figure 29. This comparison shows the CO_2 reduction which is a consequence of the utilization of Geothermal Heat.

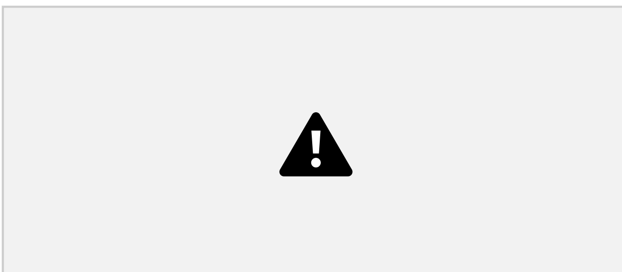


Figure 29: Difference between Case A and Case B

Additionally, the reduction of GHE owing to the inclusion of the heat pump is shown by means of the comparison between Case B vs Case C. The equivalences of that reduction is shown in Figure 30.

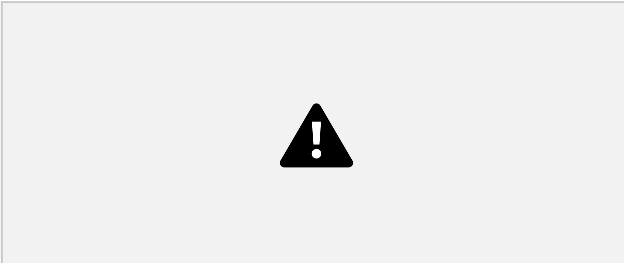


Figure 30: Difference between Case B and Case C

Finally, a summary table is presented with all the used figures in the above-detailed figures.

	Unit	Case A - Without Geothermal Energy	Case B - Without Heatpump	Case C - With 1 Heat Pump
GAS				
Yearly heat demand from boiler	*GWh/year*	113	98	92
Annual amount of gas	*N hm³/year*	14.59	12.74	11.97
Annual expenditure on gas	*USD/Year*	**-1 495 000 USD**	**-1 310 000 USD**	**-1 230 000 USD**
WATER COST				
Flow	*m³*	50	50	50
Amount per year	*m³/year*	432 000	432 000	432 000
Annual expenditure on water	*USD/Year*	**-60 000 USD**	**0 USD**	**0 USD**
ELECTRICITY				
Total electrical consumption	*MWh/year*	454	616	1160
Annual expenditure on electricity	*USD/year*	**-20 000 USD**	**-25 000 USD**	**-45 000 USD**
ANNUAL EXPENDITURES		**(A)**	**(B)**	**(C)**
Total operative expenditures on Gas, Water and Electricity	*USD/year*	**-1 575 000 USD**	**-1 335 000 USD**	**-1 275 000 USD**
CO_2				
Total CO_2 emissions	*$tCO_2eq/year$*	**28 700**	**25 100**	**23 900**

Table 9: Summary of results

In the next section, the economic evaluation is presented to evaluate the convenience of each case.

3.2 Economic evaluation

Finally, the net present values of the required investments and future expenditures were considered to evaluate the investment in a specific period. This project implies the investment and saving in expenditures during 15 years, the NPV for each year and case. The result of the tables is summarised in the following graph.

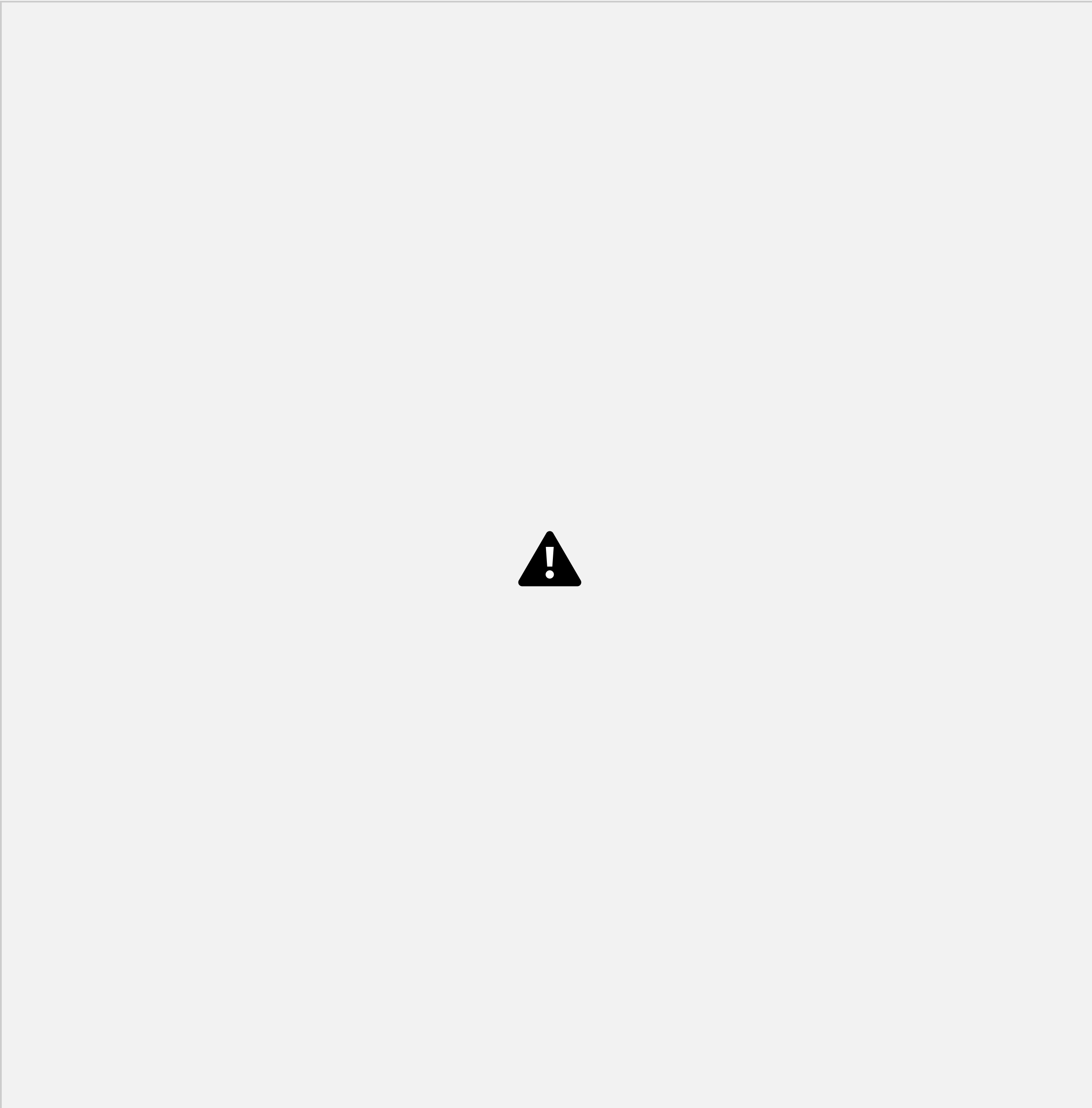


Figure 31: NPV of the three alternatives

3 Results

As shown in Figure 31, the net present value is higher and considerably more convenient for the case of using geothermal energy. In the case of the heat pump analysis, the economic evaluation includes already the investment of the equipment.

Finally, the table used for the obtention of the presented graph is shown below.

NPV to evaluate geothermal utilization	NPV
Case A - Without geothermal	-$ 18 250 000
Case B - Without HP	-$ 15 530 000
Case C - With 1 Heat Pump	-$ 15 230 000

Table 10: NPV results

The alternative of not using geothermal water can be evaluated by analysing these figures. This evaluation represents a way to determine how much such a project could save in future expenditures. This information gives an idea about the monetisation of the savings such a project could imply. As it can be seen above, the net present value of the alternative using geothermal heat is 15 % lower and with a heat pump 17 % smaller.

It is important to re-emphasise that these calculated differences do not include the costs of drilling new wells and applying the required maintenance during the proposed period. However, these calculations orient the investor in the magnitude order, which could have been covered in a project requiring a new geothermal well. For instance, if comparison between Case A and Case B is considered, it can be concluded that an amount of approximately 2 700 000 USD for the net present value of investment, future maintenance and repairs expenditure of a new geothermal well could be covered. In addition, the 300 000 USD difference between Case B and Case C indicates the convenience of including the heat pump in such a project.

Moreover, this economic evaluation does not include into analysis the carbon pricing due to the GHE reduction. Therefore, this could play an essential role in the project evaluation because of the global trend and image benefits that would bring to the company.

4 Conclusions

In Bahía Blanca, the geothermal aquifer has been used for many decades and represents an essential and strategic resource for the region. According to the situation explained throughout this paper, drinkable water represents a scarce resource in the area. Thus, every project linked to the freshwater provision might have a significant social repercussion.

Additionally, it is crucial to outline that this water necessity could also be solved by combining different projects. Therefore, the aquifers exploitation might also play a salient role in the possibilities for Bahía Blanca within a combination of different water sources.

The deep hydrothermal aquifer has been exploited since 1915, and from that moment, many wells have been dug. Nowadays, some are closed, but others are still being used for water provision. Nevertheless, only a few takes advantage of the heat content.

This thesis displays how vital geothermal water is for the analysed industrial case. As detailly explained throughout the document, the utilisation of geothermal heat has a significant impact on the environment because of its carbon dioxide emission reduction and generates considerable economic savings. However, such an engineering concept implies associated costs, whose payback was analysed.

On the one hand, for the case of evaluating the implementation of a heat pump, due to the economic analysis, it can be concluded that the investment could be paid back. As shown above, the positive net present difference of 300 000 USD shows that the investments for the heat pump would be covered.

On the other hand, for the case of evaluating the importance of using geothermal water against not using it, this analysis shows the central role that geothermal water represents in the company's processes. Considering the comparison of the obtained NPV, it is possible to conclude that such a project could even cover necessary investments of around 2 700 000 USD.

Additionally, if the greenhouse emission reduction were included in the evaluation, it would have a positive impact on the economic aspect and the company's image. In this case, the equivalence would be comparable to a yearly reduction of 1600 tonnes of recycled waste, to the CO_2 capture of 2500 hectares of forest or more than the yearly emission of 1000 vehicles.

Nonetheless, due to the area's geology, the exploitation of the geothermal aquifer has associated risks that should be detailly evaluated before prospecting a new geothermal well.

4 Conclusions

Finally, this evaluation could also help local authorities, who want to preserve the aquifers, to value the wells as potable water and renewable energy source.

In the same way, these projects could represent an important opportunity for food-producing companies looking for international markets in a globalised world with well-informed consumers seeking CO_2 neutral products.

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8 Appendix

Constants used for the mass and energy balances

Constants		
CP Water 20 ºC	4.182	kJ/(kg*K)
CP Water 25 ºC	4.178	kJ/(kg*K)
CP Water 30 ºC	4.176	kJ/(kg*K)
CP Water 40 ºC	4.175	kJ/(kg*K)
CP Water 50 ºC	4.178	kJ/(kg*K)
CP Water 100 ºC	4.211	kJ/(kg*K)
CP Water 110 ºC	4.222	kJ/(kg*K)
CP Water 120 ºC	4.232	kJ/(kg*K)
CP Water 130 ºC	4.2445	kJ/(kg*K)
CP Water 140 ºC	4.257	kJ/(kg*K)
Density Water 10 ºC	999.7	kg/m3
Density Water 20 ºC	998.2	kg/m3
Density Water 30 ºC	995.7	kg/m3
Density Water 50 ºC	988.1	kg/m3
Density Water 120 ºC	943.5	kg/m3
Density Water 130 ºC	934.9	kg/m3
Density Water 140 ºC	926.3	kg/m3
Density Air 10 ºC	1.246	kg/m3
Density Air 20 ºC	1.204	kg/m3
Density Air 30 ºC	1.164	kg/m3
Density Air 40 ºC	1.127	kg/m3
Density Air 50 ºC	1.093	kg/m3
Density Air 60 ºC	1.060	kg/m3
Density Air 70 ºC	1.030	kg/m3
Density Air 80 ºC	1.000	kg/m3
CP dry Air 0 ºC	1.011	kJ/(kg*K)
CP dry Air 10 ºC	1.0115	kJ/(kg*K)
CP dry Air 20 ºC	1.012	kJ/(kg*K)
CP dry Air 30 ºC	1.013	kJ/(kg*K)
CP dry Air 40 ºC	1.014	kJ/(kg*K)
CP dry Air 50 ºC	1.015	kJ/(kg*K)

CP dry Air 60 ºC	1.017	kJ/(kg*K)
CP dry Air 70 ºC	1.018	kJ/(kg*K)
CP dry Air 80 ºC	1.019	kJ/(kg*K)

Case A – Winter

Case A – Summer

Case B – Winter

Case B – Summer

Case C – Winter

Case C – Summer

Economic evaluation figures

Used parameters for economic evaluation					
Discount rate	3.0 %				
Heat pump annual maintenance rate	1.5 %	*of heat pump cost*			
Heat pump annual repairing rate	1.5 %	*of heat pump cost*			
Cooling towers maintenance	50 %	*of heat pump's repairing and maintenance*			
Auxiliary items cost	10 %	*of heat pump cost*			
Engineering cost	8 %	*of heat pump cost*			
One heat pump HHR1000 cost	250 000	€	300 000	USD	
Exchange rate USD/€	1.19				
Round out factor:	10 000 USD				

Case A - Without Geothermal Energy	*(in USD)*									
	Year 0	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	
Total operative expenditures on Gas, Water and Electricity [USD/year]		-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1
Heat pump	0									
Auxiliary items	0									
Engineering	0									
Year expenditures	0	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1.575.000	-1
NPV	-18.250.000									

Case B - Without Heat Pump	*(in USD)*									
Total operative expenditures on Gas, Water and Electricity [USD/year]	**Year 0**	**Year 1** -1.335.000	**Year 2** -1.335.000	**Year 3** -1.335.000	**Year 4** -1.335.000	**Year 5** -1.335.000	**Year 6** -1.335.000	**Year 7** -1.335.000	**Year 8** -1.335.000	-1
Heat pump	0									
Auxiliary items	0									
Engineering	0									
Maintenance and repairs		-4.500	-4.500	-4.500	-4.500	-4.500	-4.500	-4.500	-4.500	
Year expenditures	0	-1.339.500	-1.339.500	-1.339.500	-1.339.500	-1.339.500	-1.339.500	-1.339.500	-1.339.500	-1
NPV	-15.530.000									

Case C - With 1 Heat Pump	*(in USD)*									
	Year 0	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	
Total operative expenditures on Gas, Water and Electricity [USD/year]		-1.275.000	-1.275.000	-1.275.000	-1.275.000	-1.275.000	-1.275.000	-1.275.000	-1.275.000	-1
Heat pump	-300000									
Auxiliary items	-30000									

Engineering	-24000									
Maintenance and repairs		-9.000	-9.000	-9.000	-9.000	-9.000	-9.000	-9.000	-9.000	
Year expenditures	-354.000	-1.284.000	-1.284.000	-1.284.000	-1.284.000	-1.284.000	-1.284.000	-1.284.000	-1.284.000	-1
NPV	-15.230.000									

The Microsoft Excel's file can be found in the following link:

https://docs.google.com/spreadsheets/d/1NLrf5kUXvVAcRI2XySkYHzurtMKEqi3r/edit?usp=sharing&ouid=117139712982844104346&rtpof=true&sd=true