ASSESSMENT OF GEOTHERMAL HEAT PUMP HEATING SYSTEMS IN COYHAIQUE CITY, CHILEAN PATAGONIA

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ABSTRACT

Coyhaique is the capital city of the Aysén region, Chilean Patagonia. The city, one of the most polluted in the country, was classified as a saturated area with respect to particulate matter by August 2012. The main source of pollution is the burning of firewood for heating purposes. Therefore, we propose Geothermal Heat Pumps (GHPs) as a renewable and environmentally friendly choice for heating.

We carried out a technical and economic assessment of the GHPs functioning for 9 types of houses. We considered a horizontal closed loop system as the geothermal collector. The Coefficient of Performance (COP) based on the temperature at 1.45m depth is 3.97.

The operational cost of GHPs in Coyhaique is the lowest, among the options analyzed in this work. Therefore, GHPs are a good option for reducing the particulate matter emissions in Coyhaique. However, the high initial investment for GHPs is an economical barrier, which must be reduced to encourage the introduction of the technology.

1. INTRODUCTION

1.1 Air quality in Coyhaique city

Coyhaique is the capital city of the Aysén region, Chilean Patagonia. Actually, there are ~ 61.081 inhabitants living in the city (Subdepartamento de demografía y vitales, 2009).

By 2012, the city was said to be saturated in coarse particulate matter (PM10, particles with a diameter ≤ 10 μm). The Chilean standard requires a PM10 concentration of lower than 50 μg/m^{3}N for the annual average, and lower than 150 μg/m^{3}N for the daily P98 (Departamento de Economía Ambiental 2014).

From 2010 to 2013, the annual and daily concentrations of PM10 were respectively 70%, and 135% higher than Chilean standard (Figure 1 & 2). The main source of PM10 is the house heating (Figure 3), which provide 94% of the total emissions.

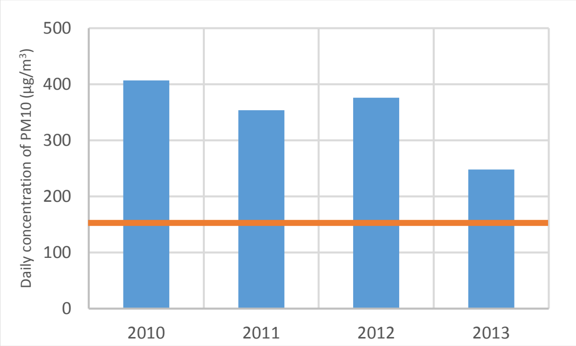

Figure 1: Daily concentration of PM10 in the air (μg/m^3) in Coyhaique during the period 2010-2013 (data from Departamento de Economía Ambiental, 2014).

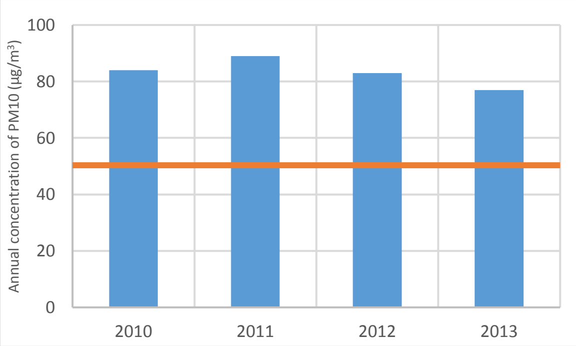

Figure 2: Annual concentration of PM10 in the air (μg/m^3) in Coyhaique during the period 2010-2013 (data from Departamento de Economía Ambiental, 2014).

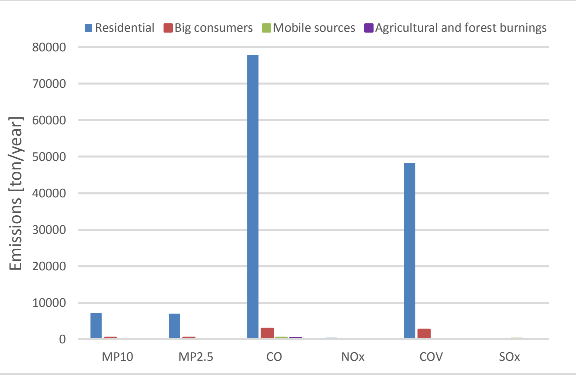

Figure 3: Different sources of emissions in Coyhaique city by 2008 (Departamento de Economía Ambiental 2014, and references there in).

1.2 Air quality in Coyhaique city

According to an opinion poll conducted in 2009, 94% of houses uses wood for heating and cooking purposes (Departamento de Economía Ambiental, 2014 and references there in). In fact, there are ~23,000 stoves and/or kitchens, which burn wood (Table 1).

Device	Percentage	Number of devices
Kitchen and stove (same device)	37.6	8,648
Kitchen	34.9	8,027
Stove	24.4	5,612
Kitchen and stove (different devices)	2.7	621
Fire place	0.4	92
Total	**100**	**23,000**

Table 1: Devices for heating and cooking using wood as fuel in Coyhaique, 2008 (Ministerio del Medio Ambiente 2015 and references therein).

1.3 Decontamination program

On 28th March of 2016, a decontamination plan for Coyhaique City and the surrounding area was proposed (Departamento de Economía Ambiental 2014). The plan aims to reduce the air pollution to achieve the Chilean standard for PM10. The implementation of the plan is going to take 10 years, with a total cost of US$ 29M (Ministerio del Medio Ambiente 2015). The decontamination plan promotes sustainable house heating, according to the following topics:

1. Improving thermal insulation for Coyhaique houses.

2. Replacement of the current polluting heating devices with much less polluting heating devices.

3. Improvement of the wood quality (less moisture content) that is used as the fuel for stoves.

4. Teaching and broadcasting to the Coyhaique community.

1.4 Geothermal Heat Pump

A Geothermal Heat Pump (GHP) uses the ground as source/sink for heating/cooling purposes (Figure 4). For heating the GHP uses electricity to concentrate, and carry heat from the ground to the house (Lund and Boyd 2016).

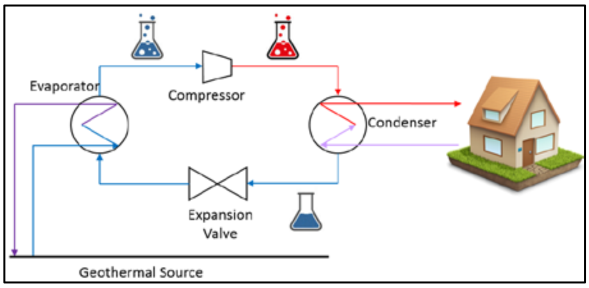

Figure 4: Geothermal heat pump used for heating purposes.

The use of a GHP for heating purposes can be summarized as follows: 1st the buried geothermal collector mines heat from ground; 2nd within the GHP the heat from the ground boils the working fluid (usually a hydrocarbon with a low boiling temperature), producing a low temperature gas; 3rd the gas is compressed producing a high temperature gas; 4th the work fluid is condensed, releasing heat because of the phase change and conduction. The heat may be distributed into the house by a radiant floor or fan coils.

2. COYHAIQUE HOUSES HEATING LOAD

2.1 Weather conditions in Coyhaique city

The heating load of houses was estimated taking into account weather conditions, in particular air temperature and solar radiation (Figures 5 & 6). These parameters were gathered from the El Claro weather station, every hour, throughout a year, starting at 24th January 2015.

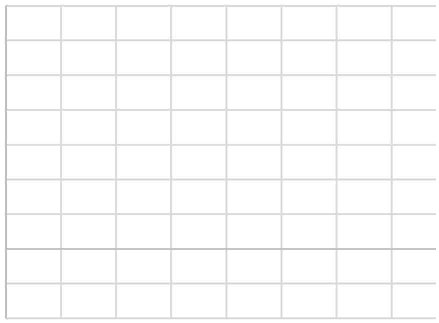

Figure 5: Air temperature in Coyhaique during 2015-2016 (Ministerio de Agricultura and INIA, 2016).

Figure 6: Solar radiation in Coyhaique during 2015-2016 (Ministerio de Agricultura and INIA 2016).

2.2 Methodology for estimating heating load

The estimation of heating load was carried out in 9 types of houses. These houses are different with respect to story numbers, window orientation, and materials (Table 2). The house features allow the estimation of the volumetric coefficient of heat exchange (Table 3). Afterwards, the thermal load is estimated from the temperature difference between the house and air, and the volumetric coefficient of heat exchange.

The Chilean standard of insulation was stipulated in 2000, and modified in 2007. Therefore, the thermal efficiencies for Chilean houses depend on the year of construction.

<table>
<tr><td rowspan="2"></td><td colspan="9">Type of house</td></tr>
<tr><td>Type 1</td><td>Type 2</td><td>Type 3</td><td>Type 4</td><td>Type 5</td><td>Type 6</td><td>Type 7</td><td>Type 8</td><td>Type 9</td></tr>
<tr><td>Story number</td><td>1</td><td>1</td><td>2</td><td>2</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td></tr>
<tr><td>Surface (m^2)</td><td>57</td><td>221</td><td>103</td><td>52</td><td>68</td><td>85</td><td>33</td><td>40</td><td>40</td></tr>
<tr><td>Type of construction</td><td>Insulated</td><td>Insulated</td><td>Insulated</td><td>Insulated</td><td>Couplet</td><td>Couplet</td><td>Couplet</td><td>Couplet</td><td>Insulated</td></tr>
<tr><td>Living area 1st floor (m^2)</td><td>56.5</td><td>114.7</td><td>63</td><td>25.99</td><td>67.7</td><td>48.4</td><td>32.47</td><td>20</td><td>39.76</td></tr>
<tr><td>Living area 2nd floor (m^2)</td><td>-</td><td>106.5</td><td>40</td><td>25.99</td><td>-</td><td>36.3</td><td>-</td><td>20</td><td>-</td></tr>
<tr><td>Area window to north (m^2)</td><td>-</td><td>28.7</td><td>10.1</td><td>3.32</td><td>3.95</td><td>5.8</td><td rowspan="8">10.38</td><td rowspan="8">4.6</td><td rowspan="8">10.38</td></tr>
<tr><td>Area window to south (m^2)</td><td>-</td><td>16.4</td><td>5.9</td><td>2.93</td><td>1.44</td><td>4.7</td></tr>
<tr><td>Area window to east (m^2)</td><td>-</td><td>7.3</td><td rowspan="2">7.7</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Area window to west (m^2)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>1.63</td></tr>
<tr><td>Area window to NW (m^2)</td><td>5.4</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Area window to NE (m^2)</td><td>7.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Area window to SW (m^2)</td><td>0.5</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Area window to SE (m^2)</td><td>3.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Wall area (m^2)</td><td>83.8</td><td>199.8</td><td>120.7</td><td>82.89</td><td>51</td><td>82</td><td>47.62</td><td>48.89</td><td>47.62</td></tr>
<tr><td>High 1st floor (m^2)</td><td>2.4</td><td>2.85</td><td>-</td><td>2.44</td><td>2.4</td><td>2.3</td><td>2.3</td><td>2.2</td><td>2.3</td></tr>
<tr><td>High 2nd floor (m^2)</td><td>-</td><td>2.88</td><td>-</td><td>2.355</td><td>-</td><td>2.3</td><td>-</td><td>2.2</td><td>-</td></tr>
<tr><td>Roof area (m^2)</td><td>60.2</td><td>121.6</td><td>63</td><td>26.48</td><td>81.7</td><td>56.5</td><td>39.76</td><td>20.57</td><td>39.76</td></tr>
<tr><td>Perimeter (m)</td><td>7.2</td><td>10.7</td><td>7.9</td><td>5.1</td><td>8.2</td><td>7</td><td>6.3</td><td>12.84</td><td>6.3</td></tr>
<tr><td>Volume (m^3)</td><td>135.6</td><td>657</td><td>361</td><td>125</td><td>162</td><td>223</td><td>91</td><td>88</td><td>91</td></tr>
</table>

Table 2: Main features of the types of houses in Coyhaique city (UNTEC, 2014 and references therein).

Type of house	Before 2000	From 2000 to 2007	After 2007	With thermal efficiency	Thermal efficiency improvement cost
	W/(m³°C)	W/(m³°C)	W/(m³°C)	W/(m³°C)	US$
1	5.865	2.665	1.374	1.222	3335
2	2.352	1.489	0.888	0.816	9429
3	2.342	1.488	0.861	0.781	4501
4	2.227	1.489	1.15	0.99	653
5	3.866	1.486	0.927	0.848	546
6	2.526	1.517	0.873	0.787	2617
7	4.117	1.952	1.042	0.935	1048
8	2.589	1.842	1.249	1.119	402
9	4.07	1.97	1.249	1.128	2086

Table 3: Volumetric coefficient of heat exchange in Coyhaique Houses, and thermal efficiency improvement costs (UNTEC 2014 and references therein).

Houses with poor thermal efficiency have 3 air circulations per hour (Ambiente Consultores Ltda. - PRIEN Universidad de Chile 2007). On the other hand, houses with good thermal efficiency have just 1 air circulation per hour, which is the target recommended by the Chilean Health Ministry (UNTEC 2014 and references therein).

Thermal gains and losses by heat transfer, and thermal losses by air circulation were estimated as following:

$$Q_{\text{gains and losses}} = G * V * (T_e - T_i) \qquad (1)$$

Here:

G: Volumetric coefficient of heat exchange $\left[\frac{W}{m^{3}°C}\right]$.
V: House volume [m^3].
T_i: Inner temperature [°C].
T_e: Outside temperature [°C].

Solar gains are estimated as following:

$$Q_{solar} = 0{,}9 * FA * S_v * I * FS * FM \qquad (2)$$

Here:

FA: Is the shadow percentage. For this work, a constant value of 1 was considered.

S_v: Is the area of the windows and outer support [m^2].

I: Solar radiation [W/m^2].

FS: Is the radiation transmission to the interior of the house. For normal windows the value is 0.87 (UNTEC 2014 and references therein).

FM: Indicates the percentage of window respect to the support. The average is 0.75 (UNTEC 2014 and references therein).

The interior energy gains by the people and household appliances are estimated as follows (UNTEC 2014 and references therein):

$$Q_{inner\ gains} = 198\ [W] + 1{,}7 * A + 1{,}7 * A \qquad (3)$$

Here:

198 [W], is thermal energy gain due to the people living in the house.

A: House area [m^2]

1,7*A: Thermal energy gains due to household appliances.

1,7*A: Thermal energy gains due to lighting units.

Finally, the house thermal load is estimated as the balance of thermal losses and gains according to the following:

$$Q_T = Q_{gains\ and\ losses} + Q_{solar} + Q_{inner\ gains} \qquad (4)$$

2.3 Considerations for heating load estimation

Thermal energy needs vary with the hour of the day. Therefore, a schedule for heating in different scenarios was considered:

- 24 heating hours: The users are all day in houses, and therefore the minimum temperature considered is 19°C, during 24 hours.
- House hours: The users are in the house after work, and therefore the minimum temperature considered is 19°C, from 18:00 to 9:00 hrs (15 hours a day).
- Office hours: The users are in offices during working hours, and therefore the minimum temperature considered is 19°C from 8:00 to 19:00 (11 hours a day).

2.4 Results for the house heating loads

The heating loads were estimated for 100% of the power demand. The heating loads for different houses, with different heating schedules, are shown in Figure 7.

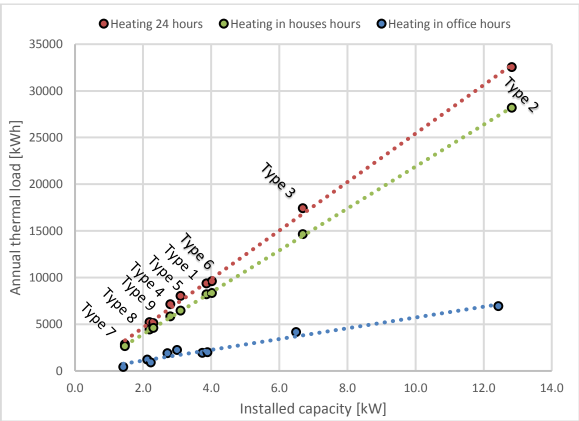

Figure 7 : Heating load for different houses in Coyhaique city, for three heating schedules.

3. GEOTHERMAL RESOURCE IN COYHAIQUE

3.1 Ground thermal properties in Coyhaique

In case of GHPs, the resource depends on ground thermal properties. In Coyhaique city, these properties were measured with a KD2Pro analyzer. For thermal conductivity we used a simple probe. For thermal diffusivity and heat capacity we used a double probe. The thermal conductivity average is 0.52 [W/m·K], the thermal diffusivity average is 0.2 [mm^2/s], and the heat capacity average is 2.58 [MJ/m^{3}K] (Figure 8).

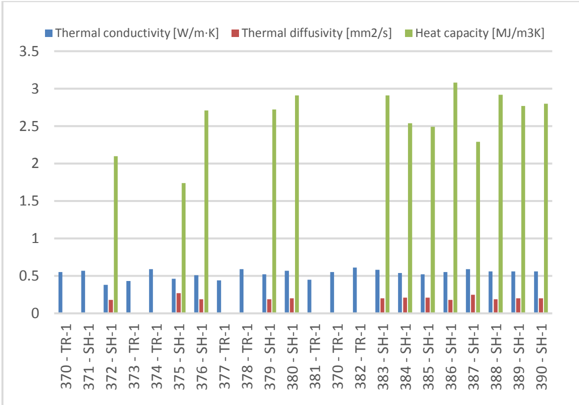

Figure 8: Ground thermal properties in Coyhaique city. TR-1 is the simple probe; SH-1 is the double probe. Data measurements were made on 20th August 2015.

3.2 Ground temperature in Coyhaique

The ground temperature in the city was measured at 1.45 m depth, with a miniaturized thermometer (ANTARES model 1854 of Datensysteme GmbH). The temperature was measured each hour, throughout a year, starting at January 21st, 2015.

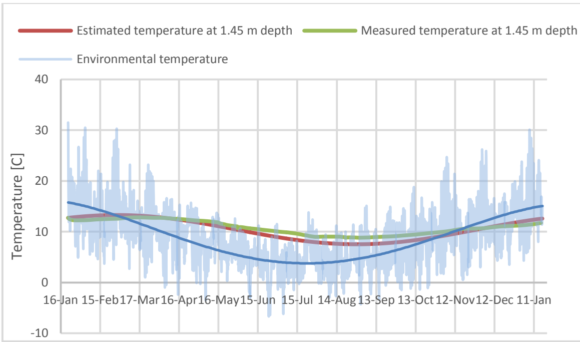

Figure 9: Ground temperature at 1.45 m depth in Coyhaique City. In addition, estimated temperature, and air temperature are shown.

3.3 Coefficient of Performance (COP)

The Coefficient of Performance (COP) of a Geothermal Heat Pump (GHP) depends on several factors. The COP is the ratio between thermal power released by the GHP, and the electrical power consumed by the system (Morrone and Coppola 2014 and references therein).

$$COP = \frac{\dot{Q}_{out}}{\dot{P}_{elec}} \qquad (5)$$

The COP is estimated from the hot temperature, in the heating focus (T_{hot}), and the cold temperature of the ground (T_{cold}), according to a Carnot cycle. In addition, an efficiency factor (α) is considered. The efficiency factor depends on design and manufacture, and ranges from 0.3 to 0.7 (Morrone and Coppola 2014 and references therein). For this work we use an α factor of 0.5 (Ochsner 2007).

$$COP = \alpha \frac{T_{hot}+273}{T_{hot}-T_{cold}} \quad (6)$$

For this study we consider a radiant floor as the heating distribution system, and so the temperature in the heating focus (T_{hot}) of the GHP is 40°C. On the other hand, the ground temperature (T_{cold}) varies seasonally throughout the year. The minimum injection temperature to the ground (T_{g1}) depends on minimum ground temperature ($T_{min\,g}$) (CANMET Energy Technology Centre - Varennes (CETC) 2005).

$$T_{g1} = T_{g\,min} - 8{,}33\,°C \quad (7)$$

The minimum temperature difference for the heat exchange between ground and GHP is 2°C, and therefore T_{cold} is expressed as following:

$$T_{cold} = T_{g1} - 2°C \quad (8)$$

To determinate the COP cycle (Figure 10), the ground temperature from 24-01-2015 to 17-01-2016 was used (Figure 9).

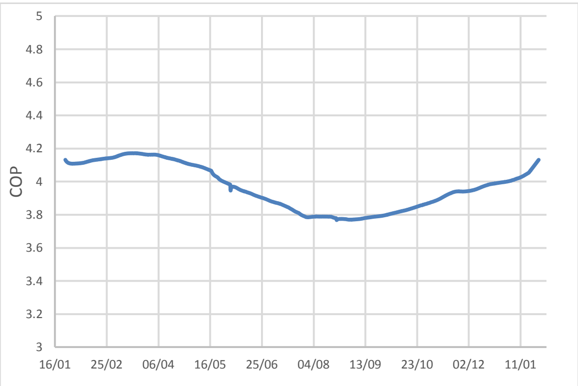

Figure 10: COP cycle in Coyhaique City.

4. ENVIRONMENTAL SCENARIO

Due to the critical pollution situation in Coyhaique City, the authorities enacted a decontamination plan to reduce the current emission from heating devices (Table 4), which use mainly wood.

The decontamination plan considers the replacement of the current heating systems by pellet stoves (Ministerio del Medio Ambiente 2015). It must be taken into account that pellet stoves reduce the local PM10 emissions, but are still a source of PM10. The measured data indicate a range of 20-80 mg/MJ, with an average of 35 mg/MJ (Nussbaumer et al. 2008).

	Emission of PM10 [g PM_{10} / kg wood]	
	Humidity 0-20 %	Humidity > 20 %
Kitchen/stove	19.2	30.9
Efficient stove	15.3	24.2
Stove	15.9	27.2
Fire place	16.6	27.9

Table 4: PM10 Emission of heating devices in Coyhaique city (UNTEC 2014 and references therein).

The emissions of pellet stoves, for the different house types, are shown in Figure 11. Even though, pellet stoves guarantee to achieve a smaller PM10 concentration in air than the Chilean standard (Ministerio del Medio Ambiente 2015), it should be considered that GHPs are a zero local emissions heating option.

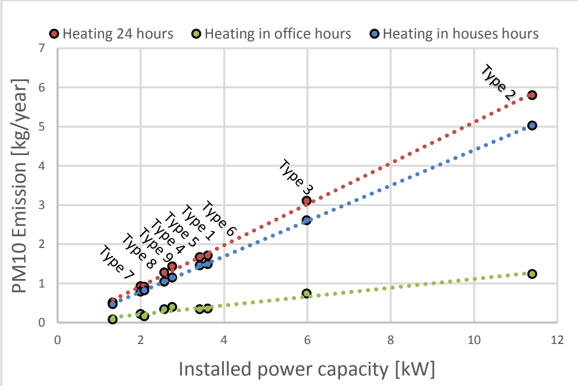

Figure 11: PM10 emissions of pellet stoves, for different house types.

The decontamination plan will reduce the annual PM10 emission to 24.3 $\left[\frac{\mu g}{m^3}\right]$ by 2025. On the other hand, the implementation of heating systems without local emission (GHP, electric heating, etc.) in all the houses should decrease the annual PM10 concentration down to 5.4 $\left[\frac{\mu g}{m^3}\right]$ (Figure 12).

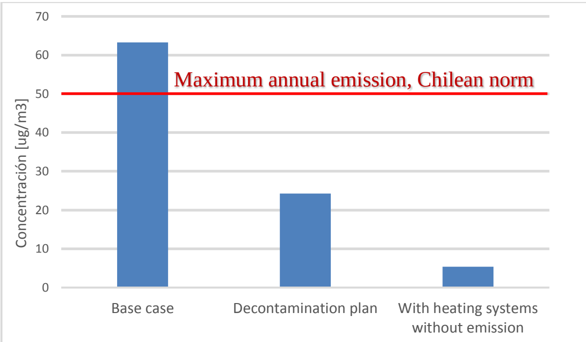

Figure 12: Annual PM10 concentrations by the end of the decontamination plan (2025) (After Departamento de Economía Ambiental 2014).

5. ECONOMIC ANALYSIS

The economic feasibility of GHP heating systems, depends on the initial investment, and operational cost compared to alternatives. For this work we consider three additional options: i) electric systems, because it is another zero local emissions heating option; ii) pellet stoves, because it is the main option of the decontamination plan (Ministerio del Medio Ambiente 2015); and liquid gas, because this heating system emits just 0.00017 $\left[\frac{\text{Kg PM10}}{\text{kg GLP}}\right]$ (Comisión Nacional de Medio Ambiente 2009); only 7% of the pellet stove emissions.

5.1 Initial investment

There is no GHP market in Chile, including Coyhaique City. Therefore GHP quotation is limited to a few companies. The initial investment ranges from 1,000 to 5,000 USD per kWt, depending on the size of the installation. Finally, to compare the Chilean setting with the international market, one USA cost reference is pointed out (U.S. Energy Information Administration (EIA) and Statistical and Analytical Agency within the U.S. Department of Energy 2015) (Figure 13).

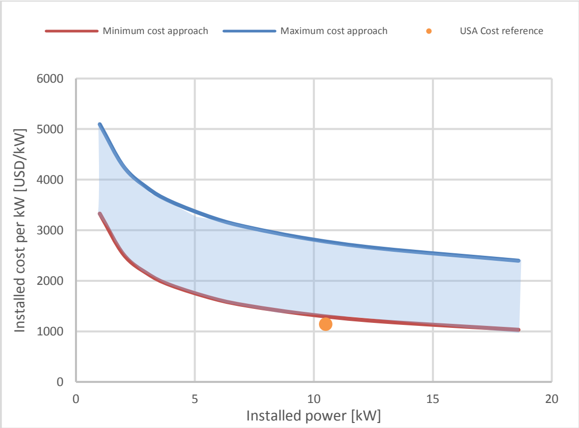

Figure 13: Initial investment for a GHP in Coyhaique City.

5.2 Operational cost

Operational cost of a GHP depends on the electricity market, because of the GHP energy consumption. Currently, the electrical energy price in Coyhaique is one of the highest in Chile (Ministerio de Energía 2016). However, from this year onwards the electricity price is going to decrease 15.9%, because of the law on equality in electrical tariffs (Comisión Nacional de Energía 2016).

There are many electrical tariffs in this electrical system. For this work we considered the BT1 tariff. This tariff is normally used in houses with electricity consumption of less than 10kWe (Superintendencia de Electricidad y Combustibles 2016).

The electricity price varies throughout a year, with a difference between the 6 hot months, and 6 cold months. During the hot period the electricity price does not vary. During the cold period, there are two different prices: if the consumption does not exceed by 20% the average consumption for the hot period, the energy base price is paid; but if the consumption exceeds by more than 20% of the average consumption for the hot period another energy price is paid (Figure 14).

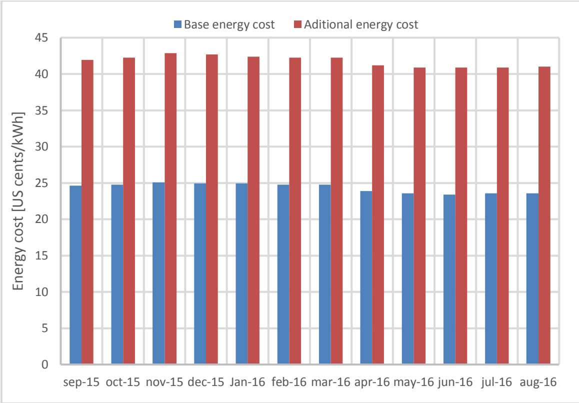

Figure 14: Energy prices in Coyhaique (EMPRESA ELÉCTRICA DE AISÉN S.A. 2016).

The electrical consumption of the GHP system is the consumption of the pumping systems of the buried geothermal collector, and the heating system, which is 22 W/kWt (Wiryadinata et al. 2016). The GHP consumption depends on the COP, and the heating thermal load of the house. Therefore, the total electrical consumption of the GHP system can be expressed as follows:

$$E_{elec}[kWh] = \frac{E_{house}[kWh]}{COP} + 0.022 * E_{house}[kWh] \quad (9)$$

Here:

E_{elec}: Total electrical consumption of the GHP system.

E_{house}: Heating thermal load of the house.

For this assessment, we considered 20 years of lifetime for the GHP (U.S. DEPARTAMENT OF ENERGY 2011). In addition, we considered that the GHP system supplies 99% of the thermal heating demand, with 95 % for the thermal efficiency of the radiant floor (Corporacion de Desarrollo Tecnológico Cámara Chilena de la Construcción - CDT 2010).

The efficiency and cost of the alternatives to the GHP system are presented below.

Heating system	Low calorific power [kWh/kg]	Efficiency [%]	Cost [USD/kg]
Pellet	4.98[1]	70[3]	0.337[5]
Liquid gas	13.64[2]	87[4]	1.66[6]
Electricity	-	95[7]	-

Table 5: Alternatives of heating systems. [1](SODIMAC 2016), [2](Lipigas 2016), [3](Ministerio del Medio Ambiente 2014), [4](DECON UC, n.d.), [5](SODIMAC 2016), [6](Internal report), and [7](Corporacion de Desarrollo Tecnológico Cámara Chilena de la Construcción - CDT 2010).

5.3 Economic results

The operational cost for a GHP system, and the alternatives, for a 24 hr. heating system are presented below (Figure 15).

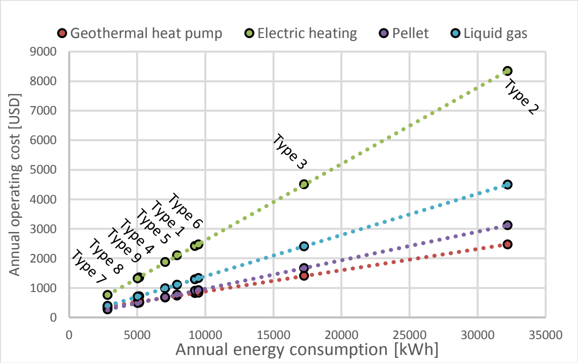

Figure 15: Operation cost for GHP system and the alternatives for a 24 hrs. heating system.

Initial investment for GHP systems are presented below (Figure 16).

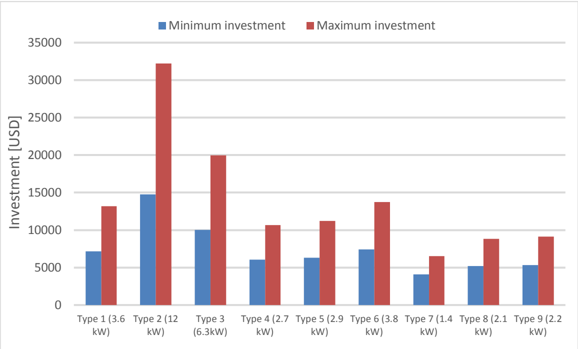

Figure 16: Initial investment for GHP systems.

The payback period of the GHP system compared to that for pellet stoves is higher than lifetime of GHP system in all cases. The payback of the GHP system compared to liquid gas stoves is lower than the lifetime of GHP for 13 cases (Figure 17).

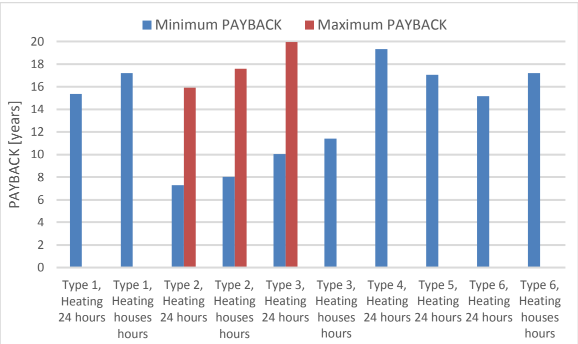

Figure 17: Payback of the GHP system compared to liquid gas stoves.

Finally, the payback of the GHP system compared to conventional electric heating systems is lower than 20 years in all cases.

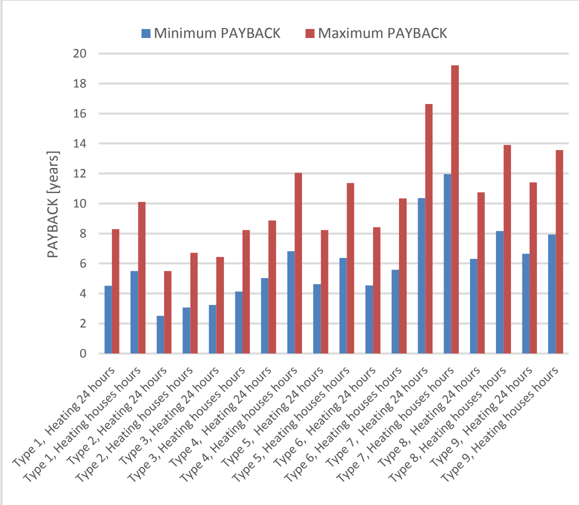

Figure 18: Payback of the GHP system compared to conventional electric heating systems.

6. CONCLUSION

Here we presented technical and economic data of the current setting of GHP systems for heating purposes. In addition, we presented the available resource for GHP, and heating thermal loads. The above are the background data for comparing GHP systems to alternatives, considered for mitigating PM10 emissions in Coyhaique city.

Concerning the geothermal resource, the average COP for the heat pump is 3.97, using a radiant floor as the heating device in house.

With the current decontamination plan, the PM10 concentration will reach 24.3[μg/m^3] by 2025, however, the implementation of heating systems without emissions decreases the annual PM10 concentration down to 5.4[μg/m^3].

The operational cost of GHP systems in Coyhaique city is the lowest of the heating systems analyzed in this work. The operational cost is even lower than operational cost of pellet stoves, which is the main option suggested in the decontamination plan for Coyhaique City.

The main economical barrier to GHP systems is the high initial investment. However, the low operation cost, and zero local emission, mean that this technology is a good option for heating houses without emissions.

Regarding the economic analysis, the pellet stove is better than GHP system. On the other hand, the economic analysis shows advantages of GHP systems compared to liquid gas and conventional electric systems.

Finally, as the initial investment per kWt is lower for bigger systems, district heating systems may be a good option for introducing geothermal energy for heating purposes in Coyhaique City.

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