A Comparative Study on the Environmental Impacts of a Binnacle Geothermal System:
Imperial Valley, CA., U.S.A. and Cerro Prieto, Mexicali Valley, BC, México

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ABSTRACT
The Cerro Prieto Geothermal Field is located in the Valley of Mexicali, Baja California, Mexico. It is the most important geothermal field in Latin America (540 MW). The geothermal system in Imperial Valley, California, U.S.A. is located in multiple sites (Brawley, Calipatria, East Mesa, and Heber & Salton Sea). Its capacity exceeds 704 MW. The development of each site on both sides of the border has experienced differences due to various factors: land rights, site preparation, type of reservoir, temperature, depth of wells, drilling, chemical composition, geothermal processes, production, utilization, legislation and environmental policy. By analyzing the two systems, great differences with regards to the environmental impacts attributable to their development can be established. After quantifying such differences in an objective manner on the basis of scientific information, measures have been provided to correct or mitigate the effects and impacts of chemical contaminants on the physical environment and the neighboring communities. Such measures were focused with an emphasis on the Mexican side.

1.INTRODUCTION
The Valleys of Imperial and Mexicali are located in the Sonoran desert; an arid region below sea level, shared by two countries. Baja California is an energy island, in the sense that it imports nearly all of its energy resources (with the exception of geothermal heat and solar energy) from out of the state. It is not connected to the Mexican mainland distribution lines and it features more linkages to the US as a result of its proximity. Imperial Valley harnesses the geothermal, solar, wind and micro-hydroelectric energy as native resources.

In the City of Mexicali, State of Baja California, the industrial and residential sectors are the most important consumers of electricity, followed by commercial users, irrigation and public lighting. This contrasts with the Imperial Valley, California, where the commercial and residential sectors consume more electricity than the industrial sector. This tendency contributes to the establishment of a development profile for each valley (Quintero and Sweedler, 2005a).

Mexicali
The Cerro Prieto Geothermal reservoir contains a liquid dominated fluid, set in a sedimentary rock environment. It is located in a pull-apart type basin, which is formed by a system featuring two faults, Cerro Prieto and Imperial faults, whereby both are part of the San Andreas Fault (Aguilar, 2010).

The Cerro Prieto Geothermal Power Plant (CPGPP) began commercial operations in 1973. Wells are drilled periodically to maintain the installed capacity and to provide support for a potential growth. According to the Mexican State-Owned Power Company (CFE, according to its initials in Spanish) a commitment has been established to provide funding for a geothermal project whose operations are planned to start up by 2017. Such project would consist of a condensing unit of 270 MWe, (Monitor Económico, 2014).

Imperial Valley
California accounts for roughly 90% of the installed capacity of geothermal energy in the USA. The main development areas are the Geyser, Imperial Valley, Salton Sea and Cosco (Lund et al, 2005). Imperial Valley generates the second largest amount of electrical power from geothermal origin in the USA, after the Geyser, at Santa Rosa, Ca., U.S.A.

The Imperial Valley geothermal facilities are located in the south of the state (Fig. 1), close to the California/Arizona border and near the Salton Sea. The power plants began operations in 1982. Proven reserves were forecasted to reach 1,105 MW, and nine years ago potential reserves were calculated to be reaching 2,330 MW (Quintero and Sweedler, 2005b).

The Imperial Irrigation District (IID), which is in charge of managing the water and power supplies, is located in the Imperial Valley and its service area encompasses 6,471 square miles (16,790 square kilometers), that includes the Imperial County and parts of Riverside and San Diego Counties. Imperial Valley features several power plants including geothermal, micro-hydroelectric, and thermal (Quintero & Sweedler, 2005a), and lately also photovoltaic and wind plants.
2. FEATURES OF THE GEOTHERMOELECTRIC SYSTEMS AT THE CA-BC BORDER.

2.1 Geological faults

Mexicali
The Cerro Prieto Geothermal reservoir is at its maturity stage, extending from the Cerro Prieto Fault to the Imperial Fault. The expansion of the reservoir to the East is currently limited by the Nuevo Leon Village and the Institute of Agricultural Sciences of the local University (Aguilar, 2010).

The field is located 30 km southeast of the City of Mexicali, capital of the state of Baja California, between meridians 115° 12’ y 115° 18’ longitude west, and parallels 32° 22’ and 32° 26’ latitude north (Fig. 2).

2.2 Well depth

Mexicali
There are currently 369 drilled wells at the CPGPP, out of which 64 are integrated into the productive processes of the various geothermal power plants in the area. Wells vary in depth with the deepest one reaching 4,400 meters. In addition, there are
currently 13 injection wells in operation that reinject a total of 63 million tons of geothermal brine per year. The remaining brine is disposed in a solar evaporation lagoon with a surface of 18.6 km² (Fig. 3) (Aguilar, 2010).

![Figure 2. Location of Cerro Prieto Geothermal Power Plant, Valley of Mexicali](image)

Figure 2. Location of Cerro Prieto Geothermal Power Plant, Valley of Mexicali

![Figure 3. Evaporation lagoon at the Cerro Prieto Geothermoelectric Power Plant.](image)

Figure 3. Evaporation lagoon at the Cerro Prieto Geothermoelectric Power Plant.

**Imperial Valley.**

Wells located at the Imperial Valley feature depths over 3,000 meters and all the geothermal fluids are injected through reinjection wells, which explains why it results in a lower environmental impact when compared to Cerro Prieto (Quintero and Sweedler, 2005a).

**2.3 Reservoir extension.**

**Mexicali.**

Since 1973, around 2,900 million tons of a binary mixture (steam and hot brine) have been extracted in an area of exploitation encompassing 18 km². In previous years, each increment in the number of wells entailed a higher steam production, but at present it is following a declining tendency as a result of the overexploitation that is taking place at the reservoir (Aguilar, 2010).

There are two main factors that define the current situation of the Cerro Prieto Geothermal Field (CPGF): (i) the declining of the geothermal reservoir due to overexploitation, and ii) a limited area for the drilling of new wells.
With respect to the land, recently a usufruct agreement, along with a pace for current drilling, was recently negotiated, whereby it was determined that the available surface is enough to drill new wells until 2017. After the land is exhausted, steam production is expected to be gradually and unavoidably reduced down to 3600 t/h, which is the equilibrium extraction rate for the reservoir (Aguiar, 2010).

**Imperial Valley.**

In 1957, at the onset of geothermal exploration in the Imperial Valley, when well Sinclair No. 1 was drilled in an effort to search for oil-gas, a natural underground volcanically heated water reservoir was found. Subsequently more wells were drilled near the Salton Sea.

Imperial Valley is part of a deep structural depression filled with sediments, and is located to the south of the border between California and Mexico. The valley is delimited by the Colorado River to the east and by the Salton Sea to the west. To the north, it is limited by the Inland Empire region and Coachella Valley that jointly make up the “Cahuilla basin or Salton Trough”; and also by Riverside County. To the south it is limited by Mexicali, Baja California. Major and minor faults cross the relatively flat surface of the valley, which is one of the more active tectonic areas of America (Lawrence Berkeley Laboratory, 1978).

In 2005, Imperial County generated 535 MW and more than 150 wells had been exploited. Geothermal development extends throughout a corridor stretching for 35 miles from East Mesa and Heber south of the valley, up to Salton Sea to the north (Fig. 1).

The Geology Studies Office and the Land Committee Administration have identified nine known geothermal areas at Imperial Valley (Lund et al, 2005).

### 2.4 Land rights

**Mexicali.**

In Mexico all the geothermal fields under exploitation are operated and managed by the federal government through the Geothermal Project Management Office of the Mexican Power Company (CFE) (Vaca, 2008), which has been expropriating many hectares affected by the operation of the CPGPP and continues to show interest in purchasing land from farmers neighboring the geothermal complex (Ortega, 2001).

The CFE has been continually purchasing more and more hectares from the villages neighboring the plant in an effort to extend the geothermal field towards the communities located to the east, getting as close to them as less than 100 meters (Azcárate, 2001).

**Imperial Valley.**

At Imperial Valley, CA, USA, land administration differs from its counterpart in Cerro Prieto, B.C., Mexico, in the sense that land belongs to private farmers, who are the ones who eventually decide whether or not to lease their land to the parties showing interest in exploiting the geothermal resource in the area for a given number of years under the umbrella of an agreement. The agreement consists in that the interested investor possesses the right to exploit the resource for 30 years, and shares a proportional part of the profits resulting from the exploitation of the resources with the land owner, and at the end of such a period, the investor returns the land to the owner, unharmed and showing no soil denitrification, in such a way that if the farmer decides to cultivate the land, it continues to be productive. There is no need to buy out the land as is the case in Mexico.

As far as the infrastructure is concerned, it belongs to private industries; for instance, four facilities at the Imperial Valley (Vulcano, Hoch, Elmore and Leathers) are held under an energy sales agreement with Southern California Edison Company pursuant to a long term purchasing agreement. Four additional units, Salton Sea 1, 2, 3 and 4, also sell energy to the aforementioned company. Additionally, energy from Salton Sea 5 and Turbo CE is sold to the power grid of California (MidAmerican Energy, 2005).

### 2.5 Geothermal process

**Mexicali.**

The geotermoelectric process at Cerro Prieto is based on a hot liquid reservoir. In 2008 there were 13 electricity generation units: four double flash with 110 MWe of capacity, four single flash with 37.5 MWe of capacity (each), four single flash with 25 MWe of capacity (each), and one single flash with a 30 MWe capacity, low pressure, that add up to 720 MWe. These power units generated 5176 GWh in 2008 with an annual capacity factor of 81.8% (Gutierrez et al., 2010). The current CPGPP capacity is 540 MWe, since a 180 MWe geothermal unit ceased operations recently.

The land neighboring the plant was used for agricultural purposes and human settlements but due to the loss of soil fertility in the area, it is no longer used for any purpose whatsoever (Quintero et al., 1993).

**Imperial Valley.**

At Imperial Valley the geothermal resource is exploited by resorting to the use of more than one process to generate electricity:

- **Binary Cycle.** Low enthalpy resources (100 to 160°C).
- **Flash Cycle and Double Flash.** Hydrothermal fluids above 360°F (182°C). Flash type plants may be used to generate electricity.

The current geothermal installed capacity at Imperial County is 704 MWe (Heber: 120.5 MWe; Hotville: 121 MWe; Brawley: 49.9 MWe; Calipatria: 412 MWe) (Ramirez, 2014).
3. ENVIRONMENTAL IMPACT.

3.1 Chemical pollutants and their effects.

Aside from generating electrical power, geothermal power plants also generate byproducts that affect the environment (air, soil, and water), such as incondensable gases (ICG), CO₂, H₂S and NH₃, as well as residual brine (Gallegos et al. 1997). Recent studies have recorded potential emissions of benzene, ammonia, methane, sulphur dioxide (SO₂), NOx and dangerous trace pollutants, including: toluene, xylene, ethylbenzene, Rn-222 and heavy metals such as As, Hg, Pb and Zn (CalEnergy Operating Corporation, 2008).

Mexicali

It is a known fact that operations of the CPGPP produce in the range of 6,400 tons /hr. of residual brine, whereby 88% of all the residual brines (Table 1) are sent to an evaporation lagoon that covers an area of 7.2 square miles (18.6 square kilometers), polluting the soil and superficial aquifers of the valley (Ramírez y García, 2004), therefore deteriorating their quality, especially with the addition of metals and no metallic minerals such as arsenic. The reinjection of only 30% of the residual brine with high concentrations of chlorides and silica (silicon dioxide) (Gutierrez and Ribo, 1994) is carried out by gravity using several dead wells (Muñoz et al., 2012).

Contamination of superficial aquifers has increased mainly due to the salinity brought about by the geothermal fluids that feature high salt content, about 60,000 parts per million (ppm) of total dissolved solids (TDS), that emerge from depths exceeding 2,000 meters. When operations began at the CPGPP, residual brine was artificially deposited at the evaporation lagoon, which was converted into the geothermal discharge zone (Ramírez and García, 2004).

Table 1. Chemical analysis of Cerro Prieto Brine. Source: Mercado et al. (1988).

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Total dissolved solids content (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>10,735</td>
</tr>
<tr>
<td>K⁺</td>
<td>3042</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>416</td>
</tr>
<tr>
<td>Li⁺</td>
<td>29</td>
</tr>
<tr>
<td>Mg</td>
<td>0.5</td>
</tr>
<tr>
<td>Sr⁻</td>
<td>3.8</td>
</tr>
<tr>
<td>Zn⁺</td>
<td>0.5</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>5.9</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1050</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>21,300</td>
</tr>
<tr>
<td>pH</td>
<td>5.50</td>
</tr>
</tbody>
</table>

Pollution is not only due to the residual brine, but also to a series of incondensable gases. They result from producing electricity, are emitted in conjunction with the steam and a variety of particles, and contribute to a major environmental deterioration as a result of the emissions containing primarily carbon dioxide, hydrogen sulphide (which is highly poisonous in high concentrations), ammonia, methane and propane (Albertson et al., 2010)

In 1997, the emission of 641,500 tons of CO₂ and 22,742 tons of hydrogen sulphides to the atmosphere of the Mexicali Valley was reported. Mexico lacks a norm to regulate the permissible emissions for H₂S (Gallegos, 1997). In view of the aforementioned, it may be assumed that, due to the unsustainable exploitation of the geothermal resource, the problem regarding the environmental impact has been accelerated (Padget, 2009).

Imperial Valley

Because of the difference in best practices, the geothermal plants at Imperial Valley account for a lower environmental impact in comparison to Cerro Prieto (Reyes et al., 2010). At Imperial Valley, practically all the geothermal fluids are reinjected, thus avoiding the residual brine having to be exposed to the air.

In some geothermal plants in Imperial Valley, solids are separated when the brine concentration is exceedingly high (Quintero and Sweedler, 2005a).

Another aspect is the strict control held over the geothermal byproducts at the Imperial Valley (Table 2), which allows for geothermal exploitation to be deemed environmentally safe and to be classified as a renewable resource.
3.2 Impacts on the physical environment

The exploration, development and utilization of a geothermal zone may have a significant impact on the physical environment surrounding the resource (Brown, 2000).

**Mexicali**

It is widely known that the technology currently being used at Cerro Prieto is not the most advanced one and that the hydrological conditions of the zone are being affected. The 14,000 tons/hr of steam that are being extracted account for much more water than the amount that is naturally fed back. Thus the existence of a geohydrological imbalance in the area has caused a small local uplift and subsidence (Fig. 4), reaching a rate of 18 cm/yr, hence affecting infrastructure, railroads tracks, irrigation canals and land of the villages nearby (Sarychikhina et al., 2011). This is mainly due to the deep natural fracture crossing the field (San Andreas Fault system) which gave way to the geothermal underground reservoir. A maximum subsidence of 62 mm during the period 1977-1979 for the Cerro Prieto geothermal field has been reported (Mercado et al., 1988).

**Table 2. Emission limits of pollutants for units 1, 2, 3, 4 and 5 of region 1 as determined by Cal Energy for the Imperial Valley. Source: IVAPCD, 2009.**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Units 1 &amp; 2</th>
<th>Units 3 &amp; 4</th>
<th>Unit 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emission limits (lb/hr)</td>
<td>Emission limits (lb/day)</td>
<td>Emission limits (lb/hr)</td>
</tr>
<tr>
<td>H₂S</td>
<td>8.4</td>
<td>202</td>
<td>12.4</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.12</td>
<td>2.9</td>
<td>0.19</td>
</tr>
<tr>
<td>SO₂</td>
<td>3.55</td>
<td>85.2</td>
<td>3.6</td>
</tr>
<tr>
<td>NOx</td>
<td>1.0</td>
<td>24.0</td>
<td>0.91</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>0.50</td>
<td>12.0</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**Figure 4** Subsidence at Cerro Prieto affects the infrastructure nearby such as the irrigation canals. The difference in height between the main and secondary canals in this site is two meters.

**Imperial Valley**

It is also a well-known fact that extraction at the geothermal wells is frequently accompanied by subsidence, which sometimes reaches dozens of centimeters. Nonetheless, at the Imperial Valley this occurrence does not pose a problem since it has not been detected so far.

At the geothermal plants located in Imperial Valley measures have been taken to diminish the noise arising from the turbine-generators, therefore disturbances are attenuated. Furthermore, at the Imperial Valley, geothermal plants are isolated from the nearest villages, so no settlements can be found in the vicinity.

3.2 Economic impact

The social and economic impacts are considered important when assessing the global effect of the geothermal development. In many cases, the socioeconomic impacts stemming from a particular development are intimately related with potential biophysical effects, and as a consequence, it is important that the environmental assessments of a geothermal development covers these issues (Brown (2000)).
Mexicali.
Cerro Prieto is the most explored, exploited, and consequently the most productive geothermal zone featuring the highest investment in Mexico (Padgett, 2009). Baja California has experienced an increase in the energy portfolio, and nowadays, electricity is produced based on geothermal resources, natural gas, fuel gas, solar, and wind. In instances where there is a surplus of electrical energy in the state of Baja California, and pursuant to agreements with American power companies, energy is exported to the U.S. Nevertheless, when required, during extremely hot summers, electricity is imported from California. The Cerro Prieto Power plant is a solid source of employment since it currently employs over 500 workers.

Imperial Valley.
The geothermal industry is responsible for 25% of the property tax base in the development of Imperial Valley. This accounts for more than $1.2 billion dollars for the 535 MW installed in the Valley, which supplies electricity to 400,000 consumers. The electricity produced is equivalent to $4x10^8$ barrels of oil per year, therefore saving 80 million dollars from non-importation. A study conducted by the Imperial Irrigation District (IID) points to the existence of a large amount of geothermal resources at the Imperial Valley. This could generate between 5,000 to 6,000 jobs in a sustainable exploitation (Joyce, 2011).

3.4 Normativity
Mexicali.
In Mexico the Secretariat of the Environment and Natural Resources (SEMARNAT, according to its initials in Spanish) is the Federal Government Institution in charge of regulating environment affairs. The Federal Attorney’s Office for the Environment (PROFEPA) is the office in charge of environmental law enforcement affairs, while the National Institute of Ecology and Climate Change (INECC) is its research branch; both are decentralized agencies. Moreover, the SEMARNAT is the agency in charge of regulating and monitoring the environmental effects of the power companies (whether private or public, like CFE). Unfortunately, the local (state and municipal) environmental agencies do not interact with the CPGPP, resulting in long times to resolve problems. In Mexico, the state and local environmental regulations derive from the General Law of Ecological Balance and Environmental Protection (Chacare et al, 2006).

PROFEPA issued an environmental assessment that corroborates the fact that at Cerro Prieto pollution resulting from chemicals and toxic metals represent a health hazard. In an official letter classified as PFBA-DBC-UDQ/MX/652/2005 and dated December 15th, 2005, the agency acknowledges that the CPGPP infringes the federal environmental regulations. Such document is under reserve, which is an indication that the health of many plant workers at the geothermal power plant may be in jeopardy.

Imperial Valley.
In the U.S. the Federal EPA has delegated the authority to issue permits to the Imperial County Air Pollution Control Department (ICAPCD) and to the San Diego Air Pollution Control District (SDAPCD). The permits would include conditions to enforce and apply federal requirements and would be subject to the supervision of the USEPA, and possibly of federal courts (KEMA Inc. 2009). In more specific terms, the most important entities that deal with issues related to air quality at the Imperial Valley are: the ICAPCD, the California Air Resources Board (CARB) and the United States Environmental Protection Agency (USEPA) at a federal level (Ramos, 2011). In the United States, the environmental regulations derive from the National Law of Environmental Policy, and in the case of California, from the Law of Environmental Quality and County Normativity (Chacare et al., 2006).

As can be seen, environmental management in the state of California, and particularly in the Imperial Valley, poses opportunities and challenges to foster a local air quality management system across the border in Mexicali (Ramos, 2011), since both communities share the same airshed.

3.5 Mitigation policy focused on the CPGPP
There are various forms of mitigation that may reduce the environmental impact currently being generated by the CPGPP. Following some technical actions that the General Director of CFE submitted before the Permanent Commission of the Honorable Mexican Congress pertaining to the Cerro Prieto Geothermoelectric Power Plant (CFE, 2011):

- Treatment of water generated at the condensation units for purposes of harnessing the water that is discharged from the power plants in order to irrigate green areas, and to be used in sanitary services and others.
- Practice hot brine reinjection with the aim of recharging the reservoir directly from the wells.
- Isolation of the steam production in new directional wells.
- Reduction of the evaporation lagoon to decrease its surface, pursuant to the criteria issued by the SEMARNAT.
- Abatement of hydrogen sulphide emitted into the environment to as much as 80% of its current emissions. The CPGPP has unsuccessfully attempted the reduction of chemical products in the stream of incondensable gases and at the cooling towers.
- Control of benzene, toluene and xylene emissions to offer guarantees and security to the population.
- Program of acoustic natural barriers in the geothermal field to diminish the continuous noise generated by planting native trees.
4. CONCLUSIONS

a) The border zone shared by the Imperial Valley and the Valley of Mexicali poses important social, economic, and environmental challenges due in part to the exploitation of the geothermal resource. Undoubtedly, both geothermal systems will continue to expand at a certain pace due to the demand of the energy sector, in particular at the Imperial Valley. In the CPGPP, expectations are not as high.

b) An important aspect that stands out is that the environmental policy currently existing in both nations, which directly targets environmental preservation and protection. It is based on the normativity that establishes maximum limits for permissible discharges of pollutants into the environment. In the case of Mexico, it is imperative to carry out readjustments to the system so that necessary measures are taken in order to contribute to the reduction of the current impact experienced at the CPGPP.

c) A sustainable exploitation of the geothermal resource should be the focused on efforts seeking to include the reinjection of all the residual brine, in the case of CPGPP, for mitigation of the damage brought about by the evaporation lagoon. Once the hot brine has been properly separated from the steam, it may potentially be used to generate electricity by resorting to a binary cycle plant, which is a common practice in the Imperial Valley.

e) At the Imperial Valley, the natural trend to produce electricity is the utilization of renewable resources like solar, wind and micro-hydraulic, and increasingly moving away from geothermal. The latter is considered to be a sound and favorable combination, which hopefully Mexicali will be able to accomplish within a short period of time, especially now that the State of California aims to generate 33% of its electrical power supply for 2020 from renewable resources.

d) Lastly, it is convenient to emphasize the existence of a wide range of job opportunities posed by the exploitation of the geothermal resources in both valleys, linked not only to the production of electricity and direct uses, but also to the quality of life of the end consumers.

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