A new series on energy innovation

Geothermal Energy

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Geothermal Energy: a Sustainable Source of Power

Over the last 30 years, geothermal energy has become a key source of electrical energy production, thanks to its cost effectiveness and technical reliability as well as its capacity to provide firm capacity with high load factors. Not only is it a clean, renewable, and environmentally-friendly technology, it is also a viable alternative that helps to diversify the energy matrix by producing constant electricity that is free of both price fluctuations that affect fossil fuels and meteorological variations[1].

More than 100 Years of Experience

In the broad sense, geothermal energy is a type of energy contained in the form of heat inside the earth. This heat—liberated by the radiogenic decay of radioactive elements—is the driver of geological processes at the regional level, including tectonic plate movements, volcanic eruptions, and earthquakes. Although this energy is practically inexhaustible, it is unevenly distributed around the planet and is generally encountered only at extreme depths, or released on the surface with such intensity that it becomes impossible to harness.

Larderello.

Source: Fabio Sartori

Therefore, when talking about geothermal energy in its strictest sense, reference is being made only to that portion of the heat that, due to its proximity to the most superficial layers of the planet, can be directly or indirectly used by humans for purposes of health or leisure, heating, industrial processes, or electricity generation.

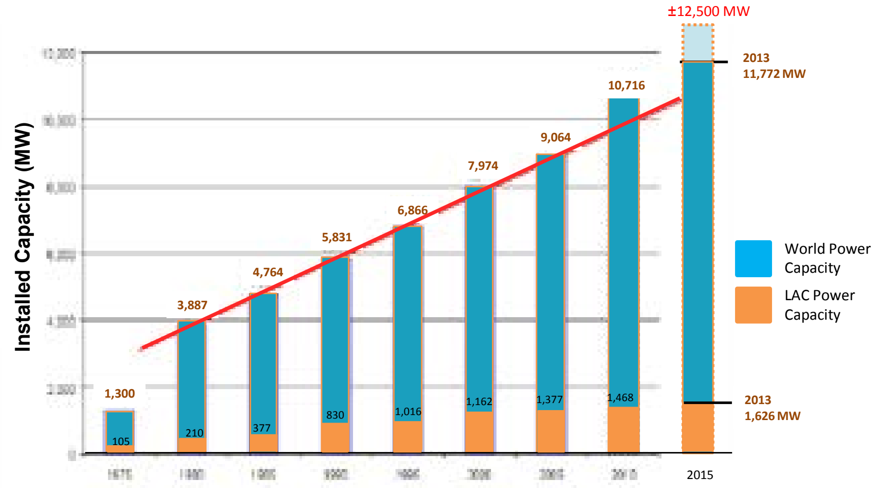
The first industrial exploitation of this energy is generally attributed to Francesco Giacomo de Larderel. In 1818, Larderel had the idea of substituting the steam used in the condensing boilers of a chemical plant in the area of Pomarance (Grand Duchy of Tuscany, in the Volterra region) with the fumarole steam that emanated naturally from the ground in the so-called "Devil's valley," located in close proximity. Once the plant began to make this substitution, the production of boric acid (an essential chemical compound in the production of soaps and beauty products) increased from 2.5 to 50 tons per year, and reached 125 tons per year in 1829. This innovation enabled the chemical plant to maintain its monopoly on the production of borates in Europe during the nineteenth century. In 1846, the village, built around the plant was given the name Larderello, in honor of its homonymous industrialist.

In the early twentieth century, the main focus in Larderello was to diversify the use of steam, whether as a source for powering boilers or for generating mechanical energy. On July 4, 1904, under the guidance of Prínce Ginori Conti, the thermodynamic energy contained in the steam was used for the first time by connecting a turbine to a generator of current that rotated inside a magnetic field. Thereafter, Larderello became the world's first producer of geothermal energy, which is also known in some countries as geothermal electrical energy. In 1913, the first commercial scale geothermal plant (250 kW) was inaugurated; by 1950, Larderello was already producing around 2 TWh/year of electrical energy. Over the following 15 years, the first pilot plants were set up in New Zealand (Wairakey in 1958), the United States (The Geyser in 1960), Japan (Matsukawa in 1966), and Russia (Pauzhetsky in 1967). In the 1970s, Mexico (1973), El Salvador (1975), Iceland (1978), and the Philippines (1979) incorporated the first geothermal electricity plants into their respective national energy matrix. Over the last 30 years, use of geothermal energy has grown constantly, and it is now consolidated as a reliable and competitive technology in 24 countries. By the end of 2013, the total installed capacity reached 11,772 MW [2].

Monte Rotondo.

Source: Enel Green Power SpA

Graph 1. World Capacity versus Installed Capacity in the LAC Region



Source: See notes 3 and 4.

Geothermal Energy in Latin America and the Caribbean

In 1973, the first geothermal plant in the Latin American and Caribbean (LAC) region, the Cerro Prieto Geothermal Power Station, went into operation in Mexico. The current installed capacity now reaches 1,626 MW in five LAC countries: Mexico (1,017 MW) [3], Costa Rica (207 MW), El Salvador (204 MW), Guatemala (48 MW), and Nicaragua (149 MW) [4]. With the exception of a small 15 MW plant on the French island of Guadalupe [5], and a pilot project in Argentina (Copahue, Argentina; 670 kW; 1988–96 [6]), there are no other plants in operation in the LAC region.

Geothermal Systems: Natural Pressure Cookers

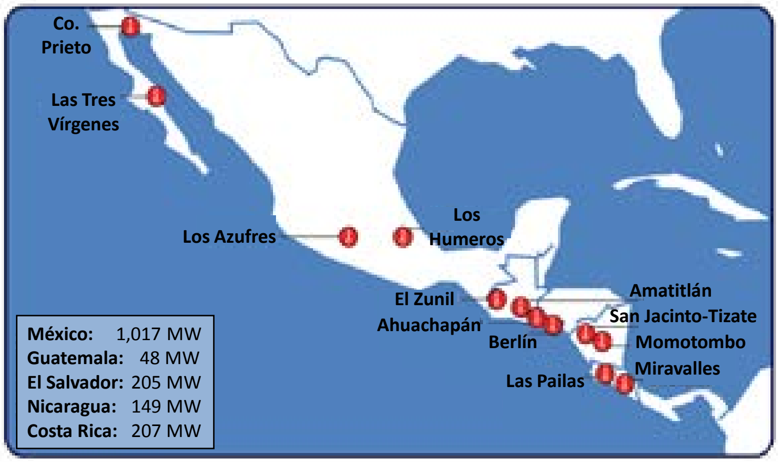
In 99% of the Earth's mass temperatures above 1000 ºC predominate and only in 0.1% the temperatures are less than 100 ºC [7]. In the most superficial part of the Earth's crust, the temperatures, heat flows, and thermal gradients (±25ºC/km) are generally unsuitable for geothermal energy exploitation.

However, there are certain places on the Earth's surface whose peculiar geological conditions allow the heat contained within the earth to accumulate in the subsoil at shallow depths (1–3km). These spots—known as geothermal fields or systems—generally mark the boundaries of the tectonic plates and are characterized by the presence of volcanic megastructures such as cones and/or calderas, intense seismic activity and numerous thermal manifestations. Precisely for this reason, Mexico [8], Central America [9], the Lesser Antilles [10] and the Andean region of South America [11], with their numerous volcanoes and thermal manifestations, are promising areas for developing geothermal technology.

To develop a commercially viable geothermal system, the following geological conditions are required: (i) a great quantity of heat stored at depths accessible to current perforation techniques; (ii) porous levels (reservoirs) containing a vector or transporter (geothermal fluid) that enables the heat to be extracted from the depths up to the surface; and (iii) more superficial impermeable levels (sealing layers or cap-rocks) that impede the migration of the geothermal fluids contained within the reservoir towards the surface.

To illustrate this, a geothermal field might be compared to a pressure cooker, where there is a source of heat (fire) that supplies energy to a reservoir (the water inside the pressure cooker), which is maintained there by the presence of a sealing layer (pressure seal) (Figure 3).

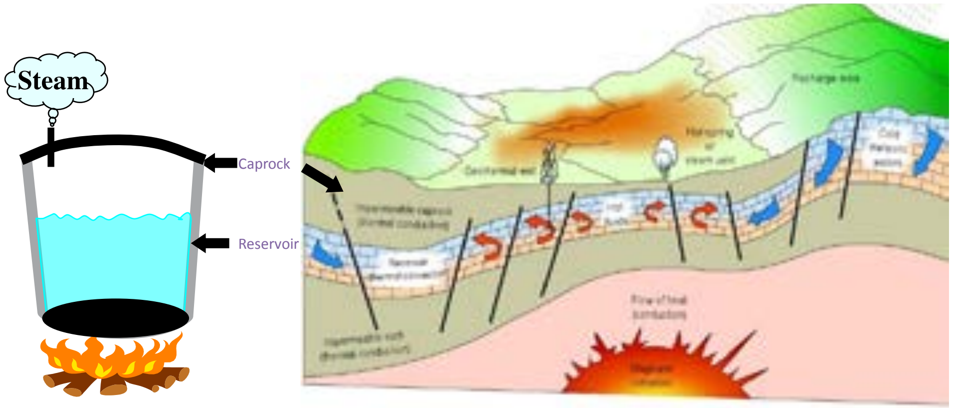
Graph 2. Geothermal Plants in Central America



Source: See notes 3 and 4.

Note: Further details regarding these plants is provided throughout the text.

Graph 3. Pressure Cooker versus a Geothermal Field



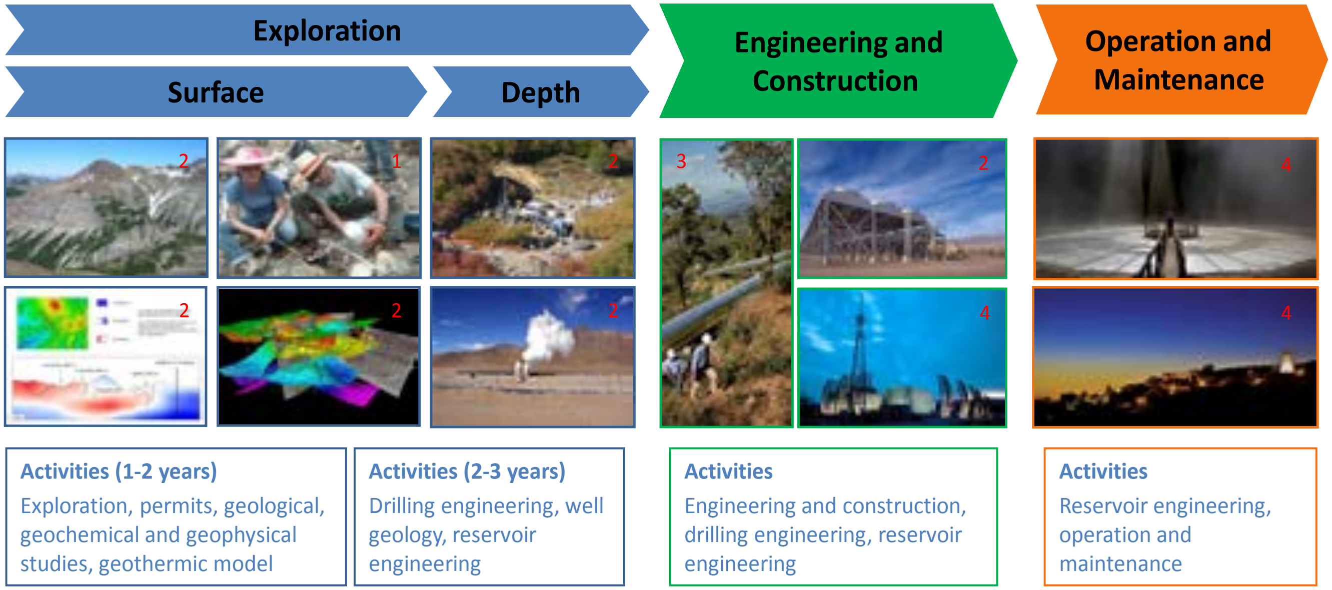
Source: The geothermal field model is taken from Dickson and Fanelli (2004).

Geothermal Projects: from Exploration to Exploitation

Schematically, a geothermal project can be divided into four main phases (Figure 4):

Surface exploration. The first phase consists in identifying and characterizing the potential system in terms of temperature, fluid typology, and spatial location. During this phase—which might take one or two years, and whose specific objective is to evaluate whether the required conditions for the existence of a high temperature geothermal system are present—the geological, geochemical, and geophysical exploration activities are carried out. Therefore, while each one of the geosciences helps to define specific technical aspects, it is necessary to integrate all the results to define a ***preliminary geothermal model***, whose purpose is to identify the main geothermal area of interest where the deep exploratory wells will be sunk. The cost of the surface exploration activities is generally reasonable and rarely exceeds US$1 to US$1.5 million. If during this phase one also considers the costs of the required permits (for concessions, as well as environmental and land leasing aspects) as well as possible market studies, then the total investment may rise to US$2.5 to US$3 million[12].

Graph 4. Geothermal Project Phases



Exploration

Surface

Depth

Engineering and Construction

Operation and Maintenance

Activities (1-2 years)
Exploration, permits, geological, geochemical and geophysical studies, geothermic model

Activities (2-3 years)
Drilling engineering, well geology, reservoir engineering

Activities
Engineering and construction, drilling engineering, reservoir engineering

Activities
Reservoir engineering, operation and maintenance

Source: See the text and notes 12–15. Photographic archives: [1] Personal, [2] Enel Green Power Spa, [3] ENEL, [4] Fabio Sartori.

Deep exploration. Once the resource has been identified, then the second phase (i.e., the drilling of the deep exploratory wells) begins. This stage generally lasts between two and three years and is vital for proving the existence of a commercially viable geothermal system. At the outset, work begins on sinking one or two slimholes (small-diameter wells) to detect the presence of the supposed thermal anomaly (deep gradient wells). Afterwards, two to four commercial (large-diameter) wells are drilled and the first assessment of the resource takes place. Although the cost of deep exploration depends on the total number and depth of the wells drilled as well as the specific logistic conditions of the site under exploration, the general rule is that a budget of US$ 1.5 to US$3 million should be allowed for each slimhole, and US$2.5 to US$3.5 million for each kilometer of commercial wells sunk. Supposing that two slimholes and four commercial wells were sunk (to a depth of 2,000m) in the deep exploration phase, the projected investment should be approximately US$23 to US$34 million. It is worth noting that early drilling activities entail the greatest investment risks, since in this phase the operator can incur the highest costs without the certainty that sufficient resources, in terms of either quantity and/or quality, will be found to make the project economically viable.

Engineering and construction. The engineering and construction phase—the duration of which depends on the size of the power station to be built—involves the following steps: (i) definition of the production and reinjection strategies, as well as the best technical solutions (engineering design); (ii) perforation of the wells required to operate the plant; (iii) preparation of the gathering system to collect and pipe the geothermal fluids; and (iv) construction of the geothermal electric power plant. In particular, during the well drilling phase, continuous and accurate analysis of the reservoir and geo-scientific data is a key activity that enables the plant to be correctly scaled (in MWe), thereby avoiding the risk of overexploiting the resource [13]. As far as costs are concerned, these can vary according to the type and size of the plant, the number of wells drilled, the logistics and the site of the project. For example, in the United States, where there are already turbine producers or makers, and an established, competitive drilling industry, the cost of a geothermal plant project can range from US$3.7 million to US$4.5 million per MW installed. In countries with logistical complications (such as, for example, when projects are implemented in mountainous areas) or where geothermal energy has yet to become a mature industry (e.g., there is a lack of turbine makers or drilling companies), costs will definitely be higher and, in some cases, might even be double.

Cerro Pabellón Project.

Source: Enel Green Power SpA

Operating the plant. The fourth and final phase consists in operating the plant and "developing" the geothermal field. At this point the geothermal fluids, which are emitted naturally by the production wells, are piped to the plant to produce electrical energy and are thereafter reinjected into the reservoir. The practice of reinjecting the fluids, which was developed for the first time in Larderello around the middle of the 1970s, has been successfully applied in numerous geothermal systems over the last 15 to 20 years. Reinjection is a best practice that not only enables the geothermal field to be correctly managed—thereby safeguarding its sustainability, the investments and the resource itself—but also helps to control and reduce the risks of environmental impacts on the surface, thereby protecting the environment [14] [15]. Furthermore, during plant operation, it is possible to further develop a geothermal field by drilling new wells. These wells aim to offset the decline in production of geothermal fluids caused by loss of pressure in the reservoir (estimated at 3% annually) and the incrustation process in the wells, which reduces the effective diameter for fluid extraction.

Based on the above, it can be concluded that: (1) the successful of a geothermal project depends on well perforation accompanied by rigorous and accurate analysis of the reservoir and geo-scientific data; (2) the reinjection of the fluids must be considered not merely as an environmental purpose, but rather a developers' right. Reinjected fluids cannot be deemed as industrial waste, as they have not undergone any chemical transformation, but rather a means of safeguarding the resource.

The Technology Used

The thermodynamic energy of the fluids is transformed into electrical energy using **back-pressure turbines** during the resource evaluation phase or **dry steam**, **flash steam,** or **binary** plants, according to the resource's characteristics (typology, composition, temperature, and pressure)[16] during the field exploitation phase.

Back-pressure turbines[17]

When employed: During the initial phase of geothermal field potential evaluation.

Description: back-pressure turbines (5 and 6 MW) are flexible, inexpensive solutions that are easy and quick to install, and are used as temporary test units, such as the kind used in San Jacinto Tizate in Nicaragua (2x5 MW) before construction began on the plant itself (72 MW)[18].

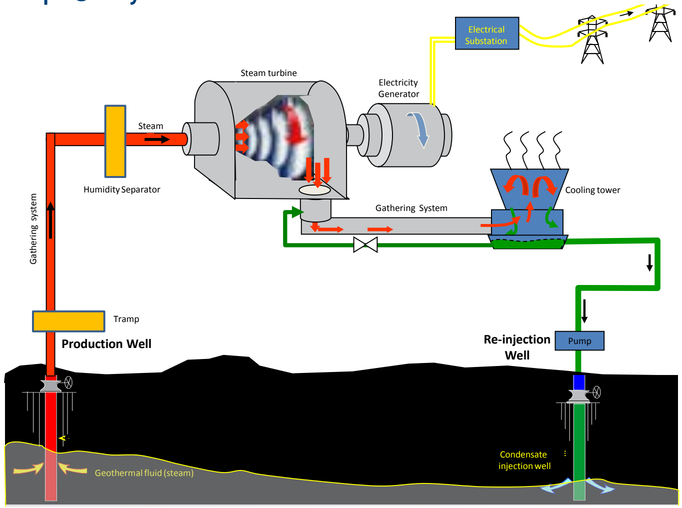
As the discharge is made directly into the atmosphere, the chemical composition of the geothermal fluids has to be accurately evaluated to avoid environmental pollution risks. This technology, however, is not economically viable if the geothermal resource is located in remote or logistically challenging areas, due to the high costs associated with building the infrastructures needed for connection to transmission and distribution grid.

Table 1. MW Installed according to Technology, Number of Plants, and Average Size

Type	Number of plants worldwide	MW installed worldwide	Average size of plants installed worldwide	MW installed in the LAC region
Dry steam	62	2,878	46.5 MW	–
Binary	236	1,178	5 MW	76
Flash steam	202	6,513	32 MW	1,285
Back-pressure	25	145	5.8 MW	90

Source: See footnote.16 Data updated to 2010.

Graph 5. Dry Steam Plant



Source: See the text and notes 16 and 19.

Dry steam plants[19]

When employed: In steam-dominated reservoirs.

Description: Conceptually speaking, these are the simplest geothermal plants: the steam produced by the wells is injected directly into the turbine[20]. Once there, taking advantage of the enthalpy difference between the entry and exit conditions, the thermodynamic energy of the steam is transformed into electrical energy. At the turbine exit, the steam is condensed in the cooling towers, and is thereafter reinjected at depth to maintain system sustainability.

The greatest advantage arises from exploiting the enthalpy difference corresponding to the conditions of the geothermal fluid inside the reservoir and the turbine exit conditions. It is worth noting, however, that geothermal steam is generally aggressive and can cause corrosion and incrustation problems that increase maintenance costs[21]. The installation costs are estimated at $1.8 to US$2.2 million per MW. There are no dry steam plants installed in the LAC region.

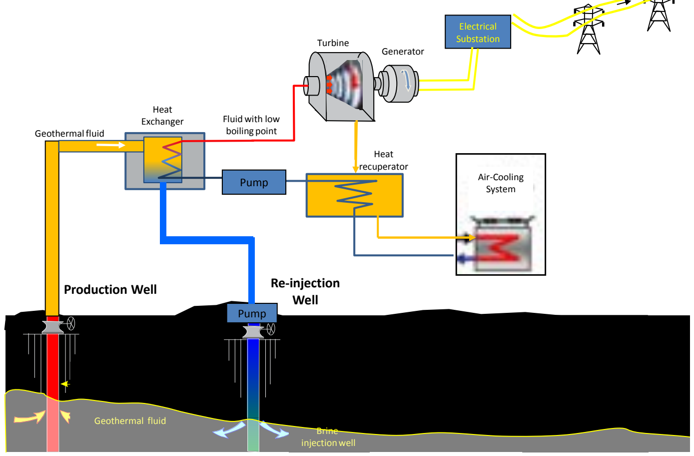
Binary plants[22]

When employed: In liquid-dominated reservoirs, with temperatures below 160 ºC.

Description: These are comprised of a heat exchanger that transfers the thermal energy of the geothermal fluid (in a liquid state) to an organic liquid with a low boiling point (isobutane or isopentane) to make it evaporate.

Thereafter, the steam from the secondary liquid is sent to the turbine where the transformation from thermal energy into electrical energy takes place, only to be once more collected and condensed and reintroduced into the heat exchanger. This completes the thermodynamic cycle. The geothermal fluid that exits the heat exchanger is routed to the wells for total reinjection [23]. The major advantage of this technology is that it can produce electrical energy by using low-enthalpy geothermal fluids (temperatures below 160º). Its major disadvantage is that the thermal performance (or efficiency) is limited, first because of the lower working temperatures of the thermodynamic cycle (100–160ºC), second because the internal consumption is high due to condensation of the secondary fluid, and third because not all of the geothermal fluid's heat/energy can be effectively used or transferred to the secondary fluid. The installation costs of a binary plant are approximately US$2.5 to US$3 million per MW installed. Examples in the region are found in Costa Rica (Miravalles, 18.5 MW, 2004), El Salvador (Berlín, 9 MW, 2007), Guatemala (Zunil, 24 MW, 1999; Amatitlán, 24 MW, 2007), Mexico (Los Azufres, 3.3 MW, 1993), and Nicaragua (Momotombo, 7 MW, 2002).

Graph 6. Binary Plant



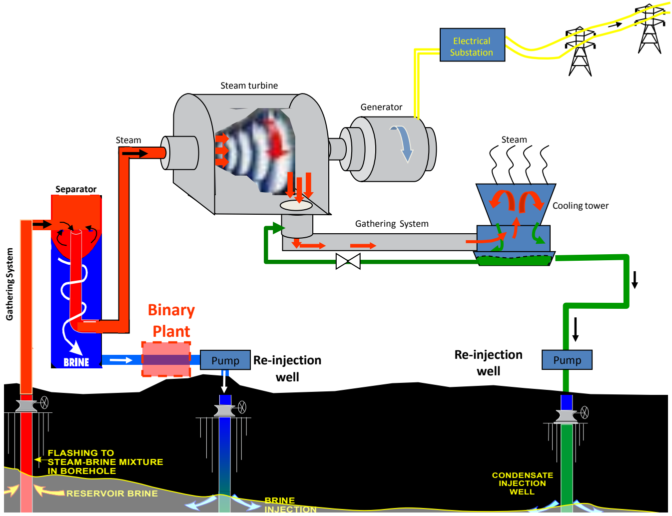
Source: See the text and notes 16,22 and 23.

Flash steam plants [24]

When employed: In liquid-dominated reservoirs, with temperatures above 160 ºC.

Description: These are the most common geothermal plants, representing approximately 60% of total installed capacity. In simple terms, in these plants the rapid extraction of fluids from the reservoir generates adiabatic decompression in the system, which engenders production of flash steam. For this to happen, the geothermal fluids produced by the wells must be comprised of a proportion of steam (20–30% of mass) and a liquid (70–80% of mass). These are separated by a high-pressure cyclone separator and are transferred to the plant to produce energy (steam phase), and to the re-injection zone to maintain system sustainability (liquid phase). After transfer to the turbine where the geothermal energy is transformed into electricity, the steam is condensed in the cooling towers and is then reinjected into the geothermal reservoir [25]. The energetic efficiency of a geothermal system exploited with a flash steam plant is lower than that one using a dry steam plant, given that the former only uses the energy power of the steam phase (20–30%), whereas the energy or heat contained in the liquid (70–80%) come back into the system via reinjection. To augment the efficiency and production of electrical energy in a liquid-dominated system with temperatures above 160 ºC, a flash steam plant can be coupled with a binary system (Figure 7). This solution means both phases (liquid and steam) can be harnessed for electrical energy production. The installation costs of a flash steam plant are an estimated US$2 to US$2.4 million per MW installed. Examples in the region are found in Costa Rica (Miravalles and Las Pailas), El Salvador (Auhachapán y Berlín), Mexico (Co Prieto, Los Azufres, Los Humeros), and Nicaragua (Momotombo, San Jacinto-Tizate),

Graph 7. Flash Steam Plant coupled with a Binary Plant



Source: See the text and note 16.

Projects and Feasibility Studies in Latin America and the Caribbean Region

Cerritos Colorados (Mexico)

In Mexico, the *Comisión Federal de Electricidad* is currently carrying out an economic and environmental evaluation of operations in the Cerritos Colorados project, located about 5 kilometers to the west of Guadalajara, Jalisco State. The project has a demonstrated potential of 75 MW [26] and favorable environmental impact assessment for the construction of a 25 MW plant [27].

Cerro Pabellón (Chile)

In the north of Chile (Region II), some 160 kilometers to the northeast of the city of Calama, *Geotérmica del Norte* is developing the Cerro Pabellón geothermal project. The company successfully concluded the surface exploration (geology, geochemical, and geophysical, as well as drilled a slimhole in 2007–08) and the deep exploration (four commercial wells) in 2009–11 [28], and confirmed the existence of a commercially viable geothermal reservoir [29]. The project has received the environmental permits to construct a 50 MW plant [30] and the corresponding transmission line (220 kV) [31].

Laguna Colorada (Bolivia)

Located in the Altiplano in the department of Potosí, Laguna Colorada is Bolivia's most advanced geothermal project. After the surface and deep exploration stages (five commercial wells) in the 1980s and 1990s [32], West Japan Engineering Consultants, Inc. presented studies in March 2008 establishing its technical, economical, and environmental feasibility [33]. According to a report by BNamericas, the Bolivian Government signed an agreement with the Japanese International Cooperation Agency (JICA) to finance a power plant due to enter production in 2019.

Las Pailas (Costa Rica)

In the region de Guanacaste of Costa Rica, the *Instituto Costarricense de Electricidad* is preparing the Geothermal Program (Programa de Geotermia), which involves three individual projects: Las Pailas 2 and Borínquen 1 and 2. These add up to a total 165 MW of new installed capacity. The technical and economic evaluation for the second 55 MW plant in Las Pailas—located in the outskirts of the Rincón de la Vieja volcano, in the geothermal field of Las Pailas—presented favorable results. With this new installation, total installed capacity in the country could reach 260 MW (Miravalles 165 MW; Las Pailas 95 MW).

Graph 8. Key Geothermal Projects in Latin America

Tolhuaca (Chile)

Located in south-central Chile (between Regions VIII and IX), the Tolhuaca geothermal project was developed between 2008 and 2012 by the Geoglobal Energy LLC company, which has successfully concluded its surface and deep exploration (geological, geochemical, geophysical, two slimholes and two commercial wells). The results indicate the presence of a geothermal reservoir with commercially viable temperatures [34]. The project has also indicated positive environmental conditions for the construction of a 70 MW plant [35]. At present, the project is undergoing an approval process by the geothermal operator, Mighty River Power [36].

Feasibility Studies

In **Honduras**, in the 1960s and 1980s, the government carried out surface exploration activities through its intermediary the *Empresa Nacional de Energía Eléctrica* (ENEE). With the support of international organizations and, in particular, Los Alamos National Laboratories, ENEE drilled three slimholes in the Los Platanares geothermal field in the mid-1980s, where a high-enthalpy reservoir was detected (T 220ºC) [37]. At present, Ormat Technologies, Inc. is working to develop this geothermal field [38].

In **Colombia**, ISAGEN successfully completed the prefeasibility studies for the Macizo Volcánico del Ruiz geothermal field, and is now preparing for the deep exploration phase, which is expected to get under way in the latter part of 2014. ISAGEN received significant support for these activities from both the Inter-American Development Bank (IDB) [39] and the Global Environment Fund (GEF) [40].

In **Ecuador**, in 2008, the *Ministerio de Electricidad y Energía Renovable* (MEER) oversaw the prefeasibility studies for four of the country's major geothermal fields (Chacana, Chachimbiro, Chalpatán, and Binacional Tufiño) [41]. These studies, which are still ongoing, will determine whether and where the deep exploration will be carried out [42].

In **Peru**, approval of the *Ley Orgánica de Recursos Geotérmicos* has opened the way for private sector investment. There are currently various exploration concessions granted to geothermal operators of international standing, such as Alterra Power Corporation, Energy Development Corporation, and Hot Rock, all of which are currently conducting prefeasibility studies.

In **the Caribbean**, especially in the Lesser Antilles, the islands of Dominica, Granada, St. Lucia, and St. Vincent and the Grenadines are sitting on geothermal resources of significant potential [43]. Dominica [44] is carrying out feasibility studies, whereas the other islands are conducting prefeasibility studies. The exception is the French island of Guadeloupe, where a geothermal plant of 15 MW, which meets around 8% of the island's total energy demands, has been operating since 1996.

Testing of Cerro Pabellón geothermal wells. *Source:* Enel Green Power SpA

It can, therefore, be concluded that the LAC region has taken some significant steps in terms of geothermal energy and that there are new and interesting prospects for the short and medium term. However, if geothermal energy is to become a new industrial reality in the region, then it must continue to receive financial, economic, and regulatory support as currently happens in Bolivia, Chile [46], Colombia [47], Costa Rica [48], and Mexico [45].

Conclusions

- Geothermal energy has become a key source of electrical energy production due to its cost competitiveness and technical reliability.
- A commercially viable geothermal system requires: (i) a large quantity of heat at depths that are accessible to current perforation techniques; (ii) reservoirs where the geothermal fluid (vector) that enables the heat to be extracted to the surface is stored; and (iii) more superficial sealing layers that stop the geothermal fluids contained within the reservoir migrating towards the surface.
- Surface exploration involves identifying and characterizing the possible geothermal field in terms of temperature, flow typology, and spatial location. The specific objective is to evaluate whether the conditions exist to exploit a high-temperature geothermal system.
- Deep exploration is indispensable, both to demonstrate the presence of a commercially viable geothermal system and for making the first estimates of the resources available in the reservoir.
- Drilling the exploratory wells is the riskiest investment activity, as the operator may incur costs without knowing whether or not it will find the resources that will make the project economically viable, in terms of quality or quantity.
- The activity of well drilling combined with rigorous and accurate analysis of the reservoir and geoscientific data are the criteria that determine the successful development of a geothermal project.
- Reinjection is an integral part of the geothermal cycle. The reinjected fluids are not deemed as industrial waste, but rather as a means to safeguard the resource.
- In geothermal plants, the thermodynamic energy of the fluids is transformed into electrical energy. The typology of the fluids stored in the reservoir determines the type of plant to be installed: dry steam, flash steam, or binary.
- If geothermal energy is to become a new industrial reality in the region, then it must continue to receive financial, economic, and regulatory support from both the public and private sectors, as currently happens in Bolivia, Chile, Colombia, Costa Rica, and Mexico.

Additional Information on Geothermal Energy

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