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Heat mining assessment for geothermal reservoirs in Mexico using supercritical CO_2 injection

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ABSTRACT

A study was conducted to assess the feasibility of using supercritical carbon dioxide injection for heat mining from geothermal reservoirs in Mexico. Traditional water-based geothermal systems require significant amounts of water, a high permeability and porous formation, and sufficiently high subsurface temperatures. sCO_2 (Supercritical CO_2) is recognized to have good mobility and flow properties for heat recovery from geothermal reservoirs. Estimations of heat mining potential using sCO_2 were performed using the TOUGH2 computer software. Simulations for three representative reservoirs in Mexico, Acoculco (Hot Dry Rock-HDR), Puruándiro (Deep Saline Aquifer-DSA) and Agua Caliente Comondú (Low Enthalpy Reservoir-LER), indicate that CO_2-based systems have better heat mining potential than H_2O-based systems. Results show enhanced heat extraction rates with sCO_2 as high as 160 percent with respect to the H_2O-based systems, with the heat mining benefit by sCO_2 increasing in inverse proportion to the site subsurface temperature. Additional simulations for twenty-one geothermal sites estimate a total power generation potential with sCO_2 of 1161 MWe. This represents a 51.4 percent additional power generation in comparison to water. Moreover, sCO_2-based geothermal systems would be able to sequester in these twenty-one geothermal reservoirs (expected 30-year life of the reservoir) approximately 72 million tons of CO_2.

1. Introduction

A recent report by the Mexican Federal Commission of Electricity (CFE in Spanish) indicates that the Mexican economy will need 45,000 MWe of additional generating capacity over the next 15 years [1]. The Mexican government has projected to meet this demand using a mix of fossil fuel-based technology, as well as renewables. The electricity sector in Mexico currently relies heavily on fossil energy sources (approximately 75 percent of the total installed capacity). One of the largest renewable energy sources available to Mexico is geothermal energy. The IGA (International Geothermal Association) has reported that Mexico has estimated geothermal reserves of approximately 8000 MWe, second in the world only to Indonesia. Mexico has a total of eight geothermal power plants, already installed and in construction, with a current installed geothermal capacity of 953 MWe (fourth in the world) [2]. Additionally, more than 1000 potential geothermal sites have been identified, with a large concentration of medium- and low-enthalpy reservoirs encompassing Mexico's volcanic region [3].

On the other side, Mexico is conscious that the needed expansion of Mexico's power generating capacity will have to be balanced with the environmental impact associated with it. In regard to carbon dioxide (CO_2) emissions, one of the greenhouse gases responsible for global warming, Mexico releases approximately 709 million tons of CO_2 annually into the atmosphere (the world's 12th largest carbon emitter), with 30 percent of this inventory coming from the electricity generating sector [4]. Meeting the forecasted future electricity demand with fossil fuels could increase Mexico's CO_2 emissions by 230 percent. Thus, adoption of green technologies — such as solar, wind, hydro, biomass, and geothermal — is a necessity to significantly help mitigate the global warming impact of an increased power generation base. The Mexican government has set targets to cut national CO_2 emissions by 30 percent in 2020 and

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50 percent by 2050. It also requires 35 percent of Mexico's energy to come from renewable sources by 2024 and allows for a national CO_2 emissions trading scheme. The combination of Mexico's power generation growth need, CO_2 emissions reduction goals, together with the large Mexico geothermal potential for power generation, offers an opportunity to develop advanced CO_2-based technologies for geothermal power generation.

Conventional geothermal power is considered to be a sustainable, renewable source of energy. Three types of technologies characterize steam-based geothermal projects: dry steam which directly uses high-enthalpy (>150 °C) steam from the ground; flash steam which uses high-temperature, pressurized water that flashes into steam; and binary cycles which use lower temperature (<75 °C) water in a heat exchanger with another fluid that has a lower boiling point than water. Geothermal power plants can feature a 30-year lifetime, have no fuel costs, have low operation and maintenance costs, and are able to produce baseload and load-following power. Furthermore, geothermal power plants working on existing steam-based technology have an average greenhouse gas emissions of 120 kg CO_2/MWh [2], which is more than 70 percent lower than the carbon intensity of oil (820 kg CO_2/MWh) or coal (950 kg CO_2/MWh). However, as carbon capture technologies for fossil-fired power plants would become cost-effective and commercial, in a CO_2-constrained word, relatively pure CO_2 is expected to become available in large quantities from fossil-fired power plants and other energy intensive industrial facilities. Instead of merely sequestering the CO_2 in a saline aquifer or using the CO_2 for enhanced oil and gas recovery, captured CO_2 could be injected into a geothermal reservoir and the heated CO_2 further used to generate additional power or to enhance the carbon capture process of the power plant or industrial facility.

The concept of using CO_2 as a working fluid to recover geothermal heat from underground reservoirs has been the subject of recent studies. This as-yet-unproven concept relies on replacing water with Supercritical Carbon Dioxide (sCO_2), which some research results have suggested would be a better working fluid than native reservoir water or brine for geothermal energy extraction [5–14]. A geothermal system utilizing sCO_2 as the subsurface heat exchange fluid in a naturally porous or fracture permeability-enhanced geologic formation would provide improved heat extraction for low temperature geothermal resources at shallower subsurfaces below the bedrock. sCO_2 is highly pressure dependent at low pressures and high temperatures, having a critical point at 31.05 °C and 73.82 bar and, despite having a smaller mass heat capacity than water; under typical geothermal formation underground conditions, has on average 40 percent of the viscosity of water and a lower density than water. With those properties, sCO_2 would provide an increased mass flow rate across an equivalent geologic reservoir and, additionally, an augmented buoyancy drive [5]. It has been suggested that CO_2-based geothermal systems could operate at 1.5 times the electricity-production efficiency of conventional water-based systems. The transport and solubility properties of sCO_2 would also help reduce contamination, scaling and degradation of power equipment found in steam-based geothermal systems.

The common concept among recent studies is based on injecting CO_2 into dry rock or hydrothermal (wet rock) geological formations, where the CO_2 fracture/fill/displaces the native reservoir fluid, mines geothermal heat and is piped back to the surface for electricity production or other applications. Part of the injected CO_2 can be geologically stored. Brown [5] presented first the use of sCO_2 in HDR (Hot Dry Rock) reservoirs in 2000. The work by Brown was based on field testing and demonstrations carried out at the Fenton Hill test site in the Jemez Mountains of North–Central New Mexico. The study by Brown concluded that for a 500 m deep HDR reservoir with an injection pressure of 300 bar, about 100,000 tons of CO_2 per year could be sequestered, in addition to about 50,000 tons of CO_2 available for closed-loop circulation.

Working on the same concept Pruess [6,7] studied the operation of CO_2-based EGS (Enhanced Geothermal Systems). In this system, sCO_2 is used as a hydrofracture media, while enhancing the efficiency of HDR geothermal energy production (in comparison to water) and allowing sequestration of CO_2. It is expected that in this type of system, sCO_2 would be injected into the hot impermeable rock, opening the crossing joints with the wellbore, forming a region of pressure dilate joints and creating a HDR reservoir. After initial formation of a two phase CO_2-water mixture in the reservoir, the passage of time will lead to the creation of a reservoir of pure sCO_2, circulating in closed-loop, while extracting heat and sequestering some CO_2 in the surrounding rock mass. In the simulation performed by Pruess [6], a reservoir thickness of 305 m was used, with reservoir rock temperature of 200 °C, injection temperature of 20 °C, fracture spacing of 50 m, permeable volume fraction of 2 percent, negligible rock permeability and 50×10^{-15} m^2 fracture permeability, 50 percent porosity in the permeable domain, and variable reservoir pressures. A five-spot well configuration was modeled, with a two-dimensional and five-point grid of 1000 m side. Conductive heat exchange with the cap and base rocks was neglected. All simulations were performed using the TOUGH2 [7] code, augmented with the EOSM fluid property module. All simulations were performed under CO_2-only or H_2O-only systems, with no consideration to mixtures of both fluids, and maintaining the injection and production bottom-well pressures constant.

The simulations performed by Pruess [8] conclude that heat extractions on EGS systems can be 50 to 100 percent larger with sCO_2 than with water. The differences become smaller with time, due to the more rapid thermal depletion when using CO_2. Mass flow rates in the CO_2 system are also larger than for water by factors as high as 3.5. Additional data from the study by Pruess [8] of CO_2-based EGS estimate that typical fluid loss rates (sequestration rates) would be in the range of 5 percent, further suggesting about 1 kg/sec/MW of sequestered CO_2. Further work by Spycher [9] on EGS systems has concluded that the production of a free aqueous phase form in an EGS operated with CO_2 will occur only after a limited number of years. It is typical to expect a useful life of geothermal reservoirs of about 25–30 years.

Randolph [11] introduced the concept of CPG (CO_2-Plume Geothermal) in which sCO_2 is used as the working fluid in a high-permeability, high-porosity geologic reservoir (typically hydrothermal or saline reservoirs) that is overlain by a low-permeability cap rock. The CO_2 displaces the native formation brine in the reservoir, heats up and then is ready for electricity generation at the surface. The sizes of these wet rock reservoirs are typically much larger than those of hydrofractured reservoirs. The simulations performed by Randolph and Saar [11,12] are an extension of the work by Pruess [6] in which the same five-well arrangement and geometry, resolved using the TOUGH2 code with the ECO2N fluid property module, was used. Different values of domain permeability were tried by Randolph, with an average value of 5×10^{-14} m^2. Other simulation parameters include a 20 percent domain porosity, reservoir pressure of 250 bar, and two reservoir assumed depths and corresponding temperatures of 4 km, 150 °C and 1 km, 100 °C.

As for the cases simulated by Pruess, CO_2 was the only fluid in the system, with no fluid or heat flow to the formation boundaries. Heat extraction rates estimated by Randolph for a 25-year average were of 62.6 MW for the deep reservoir and 64.1 MW for the shallow reservoir. A comparison was done for a comparable EGS, resulting in 47.0 MW of extracted heat. The results for the CPG systems show that the heat extraction decreases with time as the heat is depleted and the temperature at the production wells decreases with time. The work of Randolph also compares CPG CO_2-based systems vs. CPG H_2O-based systems. Cases run at different combinations of initial reservoir pressure and temperature show that for an average 25-year reservoir lifetime, the heat extraction rates for CO_2 are between 2.3 and 3.0 times larger than for the H_2O-based cases. The corresponding heat extraction ratios of CO_2 to H_2O are in the range from 4.9 to 5.5.

Salimi and Wolf [13] have presented another concept for CO_2 utilization in geothermal sites. This concept involves co-injection of CO_2 and water, to prevent drying out and over-pressurizing the reservoirs. Another advantage of this concept is related to the dissolved phase of CO_2 in water, which would avoid confinement of CO_2 to the upper part of the reservoir, decreasing leakage via the cap rock. It was recognized in the study by Salimi and Wolf that there is a problem with model formulation due to phase transition; however, self-developed model results were presented that indicate that at CO_2 mole fractions below 0.10, cumulative heat extraction from such system can be as high as 1000 TJ for 30 years.

Buschneck et al. [14] have introduced a hybrid two-stage approach to sequester CO_2 and produce geothermal energy in saline, sedimentary formations. In this concept, first brine is extracted from the reservoir to provide pressure relief for CO_2 injection; then, when CO_2 is injected and it reaches the production wells, co-produced treated brine and CO_2 become the working fluids for energy recovery. Three-dimensional model results, using the NUFT code, for reservoirs with temperatures in the 100 °C range, report heat extraction rates with this approach as large as 100 MW/m^2, with combined flow rates as high as 280 kg/s.

Finally, a recent study was presented by Zhang et al. [15], which confirms that sCO_2 has good mobility and certain heat capacity, which can be used as an alternative to water for heat recovery from geothermal reservoirs. In the work of Zhang et al. [15] different types of geothermal resources for China were assessed to screen reservoirs suitable for heat mining and geological storage by CO_2 injection, in terms of geological properties, heat characteristics, storage applicability, and development prospects. Reservoir simulations were conducted to analyze the heat extracting capacity and storage efficiency of CO_2 using a simple calculation method. The assessment results show that the recoverable geothermal potential by CO_2 injection in China is around 1.55×10^{21} J, using HDR as the main geothermal resource contributor. The corresponding CO_2 storage capacity is up to 3.53×10^{14} kg with the deep saline aquifers accounting for more than 50 percent of total. It was concluded in this study that CO_2 injection for geothermal production is a more attractive option than pure CO_2 storage due to its higher economic benefits in spite of that many technological and economic issues still needed to be solved in the future.

This paper reports the results of a study focused on assessing the feasibility of using sCO_2 injection for heat mining in geothermal reservoirs in Mexico, and compare it with that of conventional water. Estimations of heat mining potential using sCO_2 were performed using the TOUGH2 computer software. Simulations for three representative reservoirs in Mexico Acoculco (Hard Dry Rock - HDR), Puruándiro (Deep Saline Aquifer – DSA) and Agua Caliente Comondú (Low Enthalpy Reservoir - LER) are presented firstly. Additional simulations for twenty-one characterized geothermal sites in Mexico show estimation of total power generation potential with sCO_2. The paper is organized according to the following: Section 1 presents the Introduction of the paper, Section 2 presents relevant information about the status of geothermal energy in Mexico, heat mining modeling and the assumptions used are described in Section 3, Section 4 is devoted to the results and discussions and in Section 5 the Conclusions are presented.

2. Status of geothermal energy in Mexico

Geothermal energy is a source of renewable energy which has been exploited since 1959 in Mexico. Since then, Mexico has grown to become the fourth largest generator of geothermal electricity in the world with an installed capacity of 953 MWe, with one reference listing feasibility studies of potential geothermal power reserves of 3650 MWe (or 20,460 GWh of energy), enough to provide more than 12 percent of the country electricity generation. The reported Mexican cost of geothermal power generation is reasonably competitive. The 2001 cost-of-generation by CFE of their geothermal plants range from 3.29 to 4.11 c/kWh, while the cost of generation of their coal-fired, conventional oil-fired, combined cycle, hydroelectric, biomass, wind, thermal solar and photovoltaic solar power plants is 4.41, 4.42, 3.25, 4.87, 8.00, 7.00, 12.00 and 22.5 c/kWh, respectively. Despite this situation, geothermal reserves in Mexico are still underexploited, particularly low-to mid-temperature resources (<200 °C). These resources have the potential of providing for industrial and residential energy consumption, such as district heating and decentralized small-scale plants (<5 MW), working on binary cycles or with heat pump technology for use in remote rural areas of the country.

One way to classify geothermal resources is based on the nature of the reservoir. This type of classification introduces hydrothermal systems or DSA, which are highly permeable and porous and can store high-enthalpy dry steam or hot brine in the 100–300 °C range (largest proportion of exploited sites in the world by a ratio of 10:1). HDR systems, are located at deep depths (<2 km) and composed of impermeable rock which needs to undergo hydraulic fracturing for subsequent water injection for heat extraction. The other types of sites that make up the list include geopressurized systems that contain water and methane (CH_4) at temperatures in the 150 °C range and pressures of the order of 700 bar; marine systems, and magmatic systems in active volcanic sites. The current installed geothermal power generation capacity in Mexico is based on DSA hydrothermal resources of high temperature (>200 °C). Four high-enthalpy sites are currently under commercial ownership and production by CFE in Mexico. These sites are Cerro Prieto in Baja California with 720 MWe, Los Azufres in Michoacán with 188 MWe, Los Humeros in the State of Puebla with 35 MWe, and the most recent plant of Las Tres Vírgenes in Baja California Sur with 10 MWe, which started operation in 2001. In total, thirty-six units, fed by 197 wells, are installed (encompassing different types of cycles including condensing, back-pressure and binary cycles), ranging between 1.5 and 110 MWe. This installed capacity represented 7700 tons of steam per hour and 6792 GWh of electric energy in 2010. Additionally, work has started at Cerritos Colorados - La Primavera, Jalisco, for an expected installed capacity of 75 MWe. Additional geothermal projects, under an initial phase of planning/construction, include Los Humeros II, and Cerro Prieto V (under international bidding). Furthermore, exploration work is being carried out at six sites with high commercial feasibility, with objectives that include demonstration of advance binary-cycles, exploration of high temperature sites and assessment of EGS technology.

Reports on the estimate of the number of geothermal sites and possible geothermal energy potential in Mexico vary in the literature. Refs. [16–18] include the largest reported geothermal inventory for Mexico, with an estimate of more than 2300 reported geothermal manifestations, spread over 27 of the 32 Mexican states. Different evaluations of geothermal resources in Mexico have been conducted over the years. The most recent compilation of data on the geothermal potential in Mexico corresponds to a report published in 2011 by the Office of Geothermal Projects (GPG in Spanish) of CFE [18]. This work is based on an inventory of 1380 hydrothermal manifestations, which were classified according to their estimated background temperature in three temperature ranges: high (>200 °C), medium (150–200 °C) and low (90–150 °C). A Volumetric Method/Montecarlo method was used in the estimations of the geothermal potential, which computes the energy contained in the rock and fluid in the reservoir utilizing density functions to estimate the most probable value of the variables used to compute the reservoir thermal energy. Subdivisions of proven, probable and possible reserves were utilized in the evaluation. Proven Reserves (1P) are those reserves where it is estimated with reasonable certainty (90 percent probability) that the energy can be commercially recovered over a lifespan of 30 years, under current operational methods and economic conditions. Probable Reserves (2P) are those reserves with a 50 percent probability that the resource is commercially recoverable. Possible Reserves (3P) are those reserves with a probability of recuperation of at least 10 percent of the estimated geothermal energy [18,19]. The total 1P reserves found from this study total 111 MWe. Additionally, 2P reserves were estimated (using assumptions of 1 km^2 of location area, a porosity of 15 percent, and a heat recovery factor of 25 percent) at 2077 MWe, with this figure expanding to 7423 MWe if possible reserves are considered. Table 1 includes a summary of the 2P and 3P geothermal reserves for Mexico, grouped into high- mid- and low-enthalpy, using temperature ranges of >200 °C, 150–200 °C and 90–150 °C, respectively.

As part of the search for information on geothermal resources in Mexico, information was gathered from geothermal sites that have been fully characterized with physical-chemical information, suitable for numerical simulation of the process of CO_2 permeation in geothermal reservoirs. Specific characterization information was obtained for a total of twenty-one sites. These sites include one non-fractured HDR reservoir, located in the State of Puebla, and twenty hydrothermal or DSA reservoirs, ranging in reservoir temperatures from 95 to 250 °C. Table 2 includes a summary of pertinent properties of the different sites, as well as the corresponding estimated 2P power generation potential for each site (for a total of 767 MWe).

The HDR site of Acoculco has been well characterized since 1995 by temperature and pressure measurements, as well by petrographic and mineralogical analysis. Exploration wells at this site found attractive high temperatures for geothermal energy extraction as high as 260 °C at a depth of 1500 m; however, the permeability of this site is very small, at 0.01 mD. The corresponding pressure at the 1500 m depth was found to be 160 bar. The Agua Caliente Comondú reservoir is part of a series of eleven identified geothermal manifestations in Baja California; with a total probable estimated power capacity of 29.8 MWe. Comondú is the only site that has been fully characterized in terms of its properties. The temperature estimation for this site found a range of temperatures between 80 and 100 °C. Given that it was reported that a well was drilled in 1997 with a depth of 500 m, where reservoir temperatures were determined, the temperature reported from those measurements at the maximum depth was used as the nominal reservoir temperature value for this site, which is 95 °C. This site was the only considered as a LER (Low Enthalpy Reservoir). For the other DSA reservoirs, no pressure data were reported; thus, an estimated value of pressure of 100 bar was assigned to all of the DSA reservoirs, except Acoculco and Comondú.

Table 1
Geothermal potential of Mexico for probable and possible reserves [18,19].

Probable reserves (2P)		Possible reserves (3P)	
High-enthalpy	1643.94 MW$_e$	High-enthalpy	5691.79 MW$_e$
Mid-enthalpy	220.37 MW$_e$	Mid-enthalpy	881.48 MW$_e$
Low-enthalpy	212.70 MW$_e$	Low-enthalpy	849.61 MW$_e$
Total	2077.01 MW$_e$	**Total**	7422.88 MW$_e$

3. Modeling of the heat mining

Assessment modeling was conducted in this study for the heat extracting capacity of sCO_2 for different characterized geothermal sites in Mexico. The representation of the physical problem was carried out using the TOUGH2, Version 2.0 software. The TOUGH2 software, which is a general-purpose geothermal reservoir simulator developed by the LBNL (Lawrence Berkeley National Laboratory) [7] is a well-verified reservoir simulator for these types of simulations and studies. TOUGH2 is a numerical simulator designed for non-isothermal flows of multicomponent, multiphase fluids in one, two, and three-dimensional porous and fractured media. The main applications for which TOUGH2 is designed are in geothermal reservoir engineering, nuclear waste disposal, environmental assessment and remediation, and unsaturated and saturated zone hydrology [7]. Details of the governing equations, boundary conditions, assumptions and implementation corresponding to this study are given below.

3.1. Governing equations

Due to the nature of the phenomenon under study, the heat transfer process from the rock matrix to the injected fluid must be considered, based on an elemental volume approach [7,20–22]. In this way, the energy stored in the solid phase corresponds only to a fraction of the elemental volume and is transferred by diffusion, while the energy transfer in the liquid phase occurs by diffusion and convection, and corresponds to the fraction occupied by the liquid phase to the total elemental volume, see Equations (1) and (2), respectively.

$$(1-\phi)\nabla\cdot(\lambda_s\nabla T_s)+(1-\phi)\dot{q}=(1-\phi)(\rho c)_s\frac{\partial T_s}{\partial t}, \tag{1}$$

$$\phi\nabla\cdot\left(\lambda_f\nabla T_f\right)+\phi\dot{q}_f=\phi(\rho c)_f+(\rho c)_f\overrightarrow{V}\cdot\nabla T_f, \tag{2}$$

For Equations (1) and (2), λ is the thermal conductivity, T temperature, $\dot{q}$ heat generated, ρ density, c specific heat; while subscripts s and f correspond to the solid and fluid phases respectively. Additionally, ϕ is the porosity, which is defined as the ratio of the volume fraction, Vol, occupied by the fluid phase to the total volume, as described by Equation (3).

$$\phi=\frac{Vol_f}{Vol_{Total}}=\frac{Vol_f}{Vol_f+Vol_s}. \tag{3}$$

On the other hand, the advective velocity $\overrightarrow{V}$ is given by the Darcy's equation:

$$\overrightarrow{V}=-\frac{K}{\mu}(\nabla P+\rho g_z), \tag{4}$$

where K is the permeability, μ is the viscosity of CO_2, P is the unknown pressure to be determined by the flow model and g_z is the acceleration of gravity.

3.2. Boundary conditions and assumptions

In order to adapt the set of Equations (1), (2) and (4), to the problem under study, the following assumptions and boundary conditions were considered:

Table 2
Geothermal sites - summary of characterization data, from Refs. [16,18].

Reservoirs	Temperature	Pressure	Porosity	Density	Cp	Permeability	2P potential
	[°C]	[Bar]	[%]	[kg/m3]	[J/kg°C]	[mD]	[MWe]
La Soledad	210	100	10	2700	850	2.2	52
Las Planillas	240	100	13	2550	830	2.1	70
Pathé	215	100	15	2600	840	2.2	33
Araró	215	100	17	2500	840	2.0	21
Acoculco	260	160	6	2700	900	0.01	107
Ixtlán	220	100	13	2600	820	2.0	17
Los Negritos	220	100	10	2600	850	2.0	24
Volcán Ceboruco	240	100	11	2600	820	2.0	74
Graben de Compostela	225	100	10	2700	840	2.0	105
San Antonio El Bravo	215	100	15	2300	800	5.0	27
Maguarichic	155	100	15	2300	810	4.0	1
Puruandiro	165	100	15	2600	840	2.0	10
Volcán Tacana	250	100	15	2600	900	2.0	60
Los Borbollones	180	100	12	2700	1000	2.0	11
Santa Cruz de Atistique	185	100	15	2500	850	1.0	12
Volcán Chichonal	250	100	15	2600	950	2.0	46
Hervores de la Vega	220	100	12	2800	1100	2.0	45
Hervores El Molote	200	100	5	2800	950	0.3	36
San Bartolomé de los Baños	220	100	10	2500	900	1.5	7
Santiago Papasquiaro	170	100	12	2700	950	1.5	4
Agua Caliente Comondú	95	75	4	2600	900	1.5	5

All geothermal sites in this table are estimated to have a conductivity value of 2.1 W/(m°C).

1) Local thermal equilibrium exists, $T_s = T_f$
2) None of the phases generates heat
3) Properties do not vary with temperature
4) The reservoir is adiabatic at all borders
5) The wells are only location for inlet and outlet of mass and energy
6) The reservoir is considered as a rectangular volume (see Fig. 1)

Using the set of conditions stated previously, the model becomes as described by Equations (5)–(7), representing the heat transfer in a continuous medium and mixing properties. The subscript *ef* refers to the effective properties of solid fluid mixture.

$$\lambda_{ef}\nabla^2 T = (\rho c)_{ef}\frac{\partial T}{\partial t} + (\rho c)_f\left(\frac{K}{\mu}(\nabla P + \rho g)\right)\cdot\nabla T, \tag{5}$$

$$(\rho c)_{ef} = (1-\phi)(\rho c)_s + \phi(\rho c)_f, \tag{6}$$

$$\lambda_{ef} = (1-\phi)\lambda_s + \phi\lambda_f. \tag{7}$$

Additionally, the top and bottom boundaries of the domain were assumed impervious, thus neglecting heat exchange with the cap and base rocks; also, the wellbore flows were neglected for simplicity, with the evaluation of the CO_2 (and comparatively water) heat mining performance mainly depending on reservoir properties and behavior. These simplifications are analogous to the ones used in similar works reported in the literature on CO_2-based geothermal studies [8,9].

3.3. Fluid properties

In the TOUGH2 software, the governing equations for multiphase fluid heat flow have the same mathematical formulation,

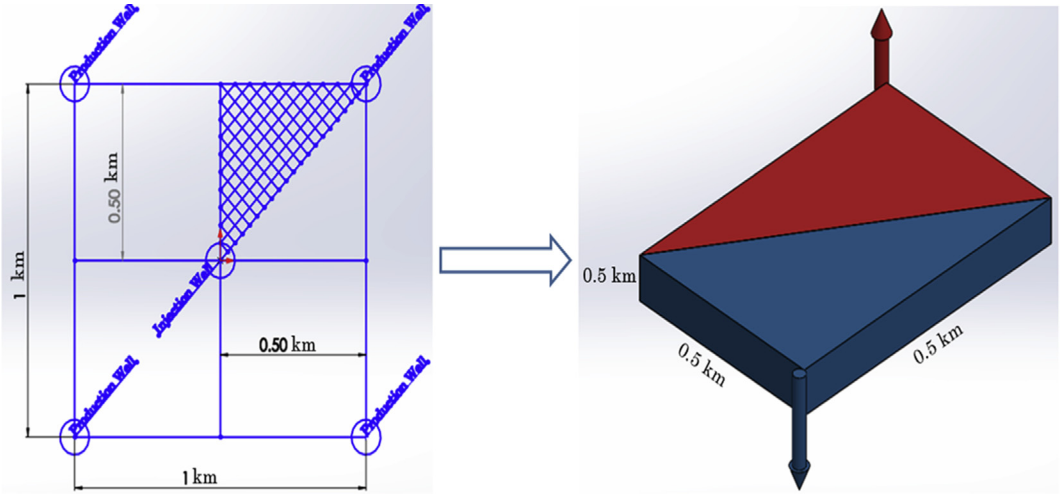


Fig. 1. Five-spot reservoir Configuration used in the simulations.

regardless of the nature and number of fluid phases and components present. Based on this, TOUGH2 has a modular architecture, in which the main flow and transport module can interface with different fluid property modules. For this study, the capabilities of the software were augmented using the equation-of-state fluid property modules EOS1 and ECO2M. While all water properties are calculated from the steam table equations in EOS1 module, the equation of state used in the ECO2M module is the Redlich–Kwong equation and the correlation by Altunin to calculate molar volumes [23,24].

The EOS1 module was used to simulate the case of single-phase pure water only, while the ECO2M module was used to simulate non-isothermal CO_2, with phase change between liquid and gaseous CO_2 solely. Thus, mixtures of CO_2 and water that would be encountered during the early development phase of a CO_2-based geothermal energy extraction system displacement of native fluid or in the periphery of the reservoir operated with CO_2 were not considered.

3.4. Postprocessing

The capabilities of the software were complemented by the post-processing capabilities provided by PetraSim [25]. PetraSim provides graphical interface for the TOUGH2 family of simulators supplied by the LBNL, handling and displaying the inputs and results in 3-D plots.

3.5. Implementation and other considerations

In order to first perform a comparative analysis of three distinct types of geothermal reservoirs in Mexico, three models were first built for a HDR, a DSA and a LER reservoir. These sites correspond to Acoculco, Puruándiro and Agua Caliente Comondú, respectively. These simulations were performed assuming a similar geological volume, consisting of an area of 1 km^2 and a thickness of 500 m. A 3-D, five-spot configuration was selected for the reservoir, since this is the geometry that has been used in similar geothermal investigations. A diagram of the five-spot configuration is included in Fig. 1. The symmetry of the computational grid reduces the modeling to 1/8th of the system domain; however, the reported data in this paper correspond to the full volume. The calculation matrix was discretized with a block number of $50 \times 50 \times 20$ and a block size of $10\ m \times 10\ m \times 10\ m$. All sites were simulated as porous media, except the HDR, which was modeled as a fractured media, using the MINC (Multiple Interacting Continua) method available in TOUGH2, where the fractures accommodate for fluid flow, while the matrix provides the thermal energy storage. The results (heat extraction and mass flow rate) were estimated for each run on a full-arrangement basis (i.e., for the entire five-spot system). Produced flow rate, F, and the net heat extraction rate, G, were calculated for the entire system as $G = F\ (h - h_{inj})$, where h is the specific enthalpy of the fluid at the production bottom-well and h_{inj} is the specific enthalpy at the injection conditions at the injection bottom-well.

A summary of the specific geophysical and chemical features of the HDR, DSA and LER reservoirs is included in Table 3. The HDR site was reported with a permeability of 0.01 mD. For the analysis of this type of site, a fractured reservoir was assumed with a fracture spacing of 75 m and a permeability of 10 mD (or $1 \times 10^{-14}\ m^2$) for the fracture and 0 for the matrix. The porosity for the HDR site was modeled with a value of 6 percent for the fracture and 0 for the matrix. The other sites were modeled with their reported permeability and porosity. The HDR initial conditions of temperature and pressure were 260 °C and 160 bar, respectively. Two cases were modeled for comparison, one case consisted of pure sCO_2, and the other case consisted of pure water. The injection temperature for both cases was 20 °C. Fluid injection and production rates were determined by specifying a 20 bar pressure difference between the injection and production wells (at the bottom hole). The wellbore flow was neglected for simplicity and to concentrate more on the comparative results from the three types of reservoirs. Simulations were run for a well life period of 40 years.

4. Results and discussions

4.1. HDR reservoir (Acoculco)

Figs. 2 and 3 include the results for the HDR reservoir for sCO_2 and H_2O, in terms of heat extraction rate and cumulative mined heat for the 40-year period, respectively. These figures compare results for both heat mining media under the same bottom hole pressure differential between injection and production wells. Production well temperature was fairly maintained at the steady production level of both fluids, for the particular pressure differential applied to the system and for the 40 years of operation of the systems, while being able to achieve a larger fluid flow with sCO_2 than with H_2O (approximately 105 vs. 40 kg/s). The heat extraction rate with sCO_2 shows to be steady at about 47 MW_{th}, while the heat extraction rate from water decreased to about 34 MW_{th} over the life of the well. The cumulative mined heat for sCO_2 is about 6×10^{13} kJ for 40 years of operation, and for water is approximately 5×10^{13} kJ.

4.2. DSA reservoir (Puruándiro)

Puruándiro was selected to represent the list of DSA reservoirs in Mexico for which a complete set of characterization data was available. Puruándiro has a reported permeability of 2 mD (or $2 \times 10^{-15}\ m^2$) and a porosity of 15 percent, which is typical of high-permeability, high-porosity hydrothermal geothermal resources found in Mexico. DSA initial conditions of temperature and pressure were set at 165 °C and 100 bar, respectively. Two cases were modeled for comparison, one case consisted of pure sCO_2, and the other case consisted of pure water. The injection temperature for water and CO_2 was set at 20 °C. The fluid injection/production rate was determined as for the case of HDR, by specifying downhole injection and production pressures, 10 bar higher and lower, respectively, than the formation pressure reported for the reservoir in the database. Simulations were performed for a well life period of 40 years.

Figs. 4 and 5 include the results for the DSA reservoir for sCO_2 and H_2O, in terms of heat extraction rate and cumulative heat mined for a 40-year period. For the driving pressure differential applied to the system (±10 bar), the flow rate of sCO_2 vs. H_2O for Puruándiro, under similar operating conditions is approximately 19 vs. 7 kg/s, respectively. The heat extraction rate was found to be approximately 45 percent larger with sCO_2 than with water, which also results in a corresponding larger cumulative mined heat by approximately 2.5×10^{12} kJ at the end of the 40-year life of the site. This significant advantage for sCO_2 can be linked to its increased value of mobility (density/viscosity), $7 \times 10^6\ (s\ m^{-2})$ for sCO_2 vs. $5.5 \times 10^6\ (s\ m^{-2})$ for H_2O at the reservoir conditions. No thermal breakthrough was noticed during the entire mining period. Thermal breakthrough occurs when the cooler injection fluid short-circuits inside the reservoir, which has a detrimental effect on the efficiency of energy production from the geothermal resource.

4.3. LER reservoir (Agua Caliente Comondú)

Results obtained for the LER of Agua Caliente Comondú, in terms of heat extraction rate are included in Fig. 6. The results for the low-

Table 3
Geological characteristics of HDR, DSA and LER sample reservoirs in Mexico.

Case	HDR (Acoculco)	DSA (Puruándiro)	LER (Comondú)
Geothermal type	Hot dry rock	Deep saline aquifer	Low enthalpy reservoir
Working fluid	sCO_2 or H_2O	sCO_2 or H_2O	sCO_2 or H_2O
CO_2 thermal conductivity [W/(m°C)]	0.0428	0.0335	0.0281
CO_2 Heat capacity [kJ/(kg°C)]	1.2472	1.2298	1.3315
Permeability [mD]	10 for fractures and 0 for matrix	2	0.5
Porosity [%]	6 for fractures and 0 for matrix	15	4
Reservoir temperature [°C]	260	165	95
Reservoir pressure [bar]	160	100	75
Injection temperature [°C]	20	20	20
Injection Bottom-Hole Pressure [bar]	170	110	85
Production bottom-hole pressure [bar]	150	90	65
Rock density [kg/m^3]	2700	2600	2600
Rock heat capacity [J/(kg°C)]	900	840	900
Rock thermal conductivity [W/(m°C)]	2.1	2.1	2.1
Assumed reservoir top layer depth [m]	2000	1500	800
Reservoir modeling element volume [m^3]	500 × 500 × 500	500 × 500 × 500	500 × 500 × 500
Well configuration	Five-spot well pattern	Five-spot well pattern	Five-spot well pattern
Perforated interval	Single layer	Single layer	Single layer
Operation time [years]	40	40	40

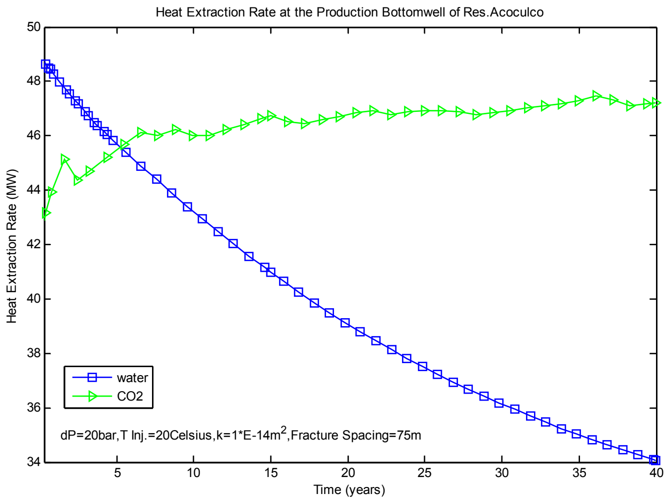


Fig. 2. Simulation results for heat extraction rate — Acoculco.

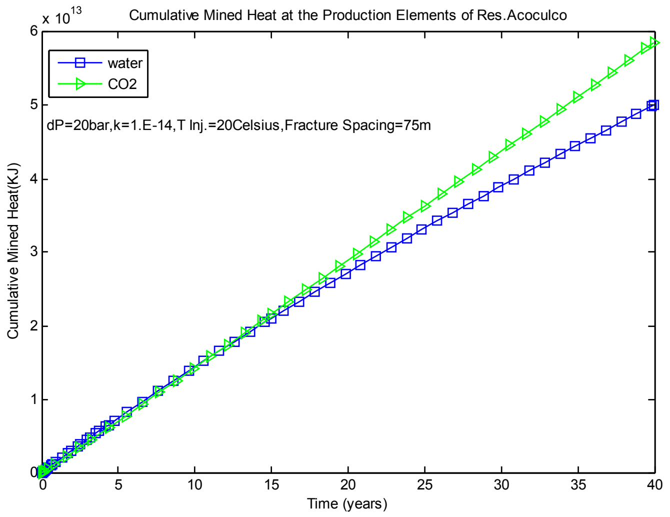


Fig. 3. Simulation results for cumulative mined heat — Acoculco.

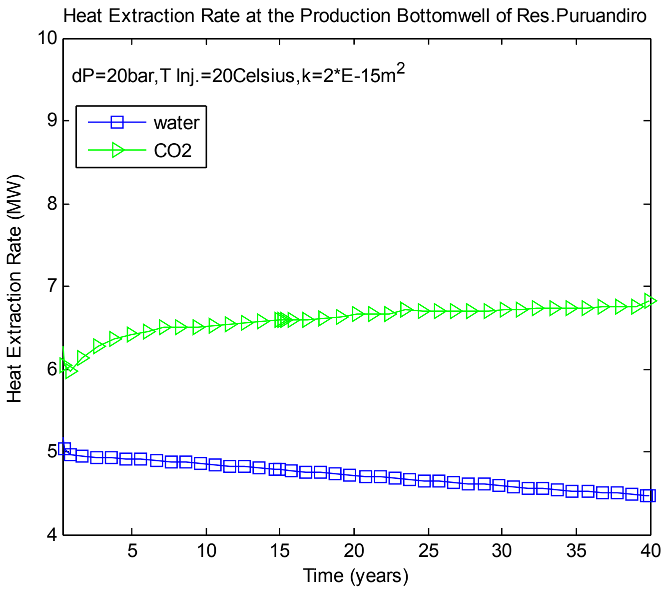


Fig. 4. Simulation results for heat extraction rate — Puruándiro.

enthalpy site, which has a reported permeability of 0.5 mD (or 5×10^{-16} m^2) and a porosity of 4 percent, and initial conditions of temperature and pressure were 95 °C and 75 bar, respectively, are very similar to the case of Puruándiro. This case with about 1/4 the flow rate for CO_2 and 1/5 the extracted heat than for DSA, down to about 1 MW. This is a result of the lower porosity, permeability and temperature of the LER. For the LER, the heat extraction rate with sCO_2 contrasts the corresponding one with H_2O, by more than doubled the extracted power in MW. Fig. 7 shows simulation results for cumulative mined heat.

4.4. Summary of HDR, DSA and LER results

A summary of the modeling results for three types of geological reservoirs with characteristics representative of Mexican sites is included in Table 4. These reservoirs correspond to a high-temperature HDR (typical of geothermal reservoirs at the center region of the republic, modeled with fractures), an intermediate-temperature hydrothermal DSA (the most abundant resource in

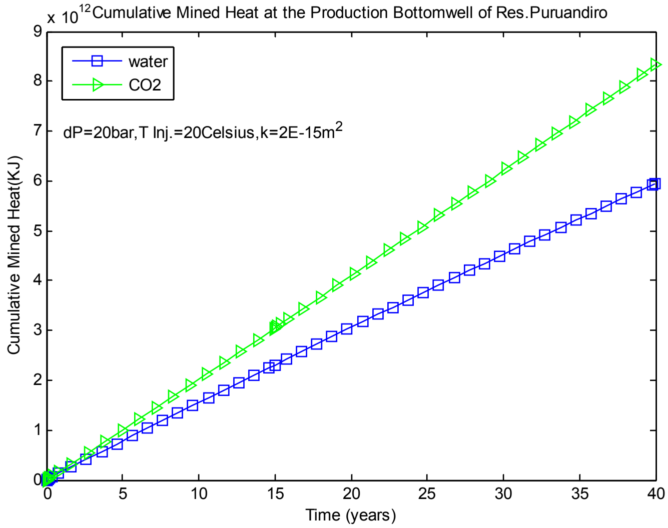


Fig. 5. Simulation results for cumulative mined heat – Puruándiro.

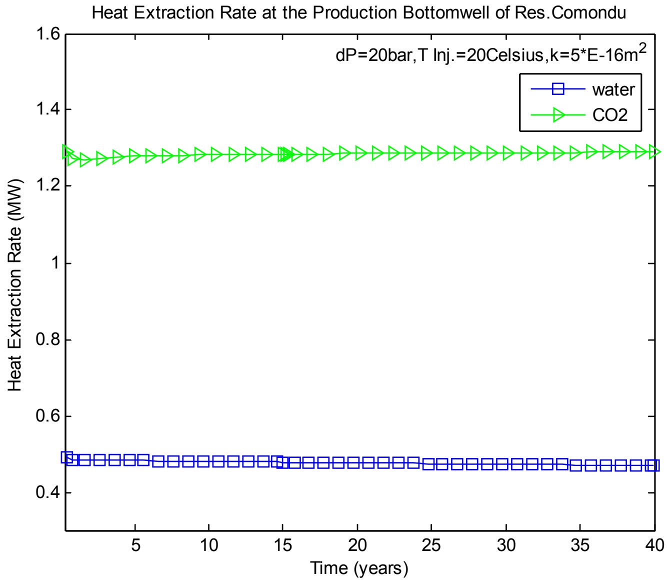


Fig. 6. Simulation results for heat extraction rate – Comondú.

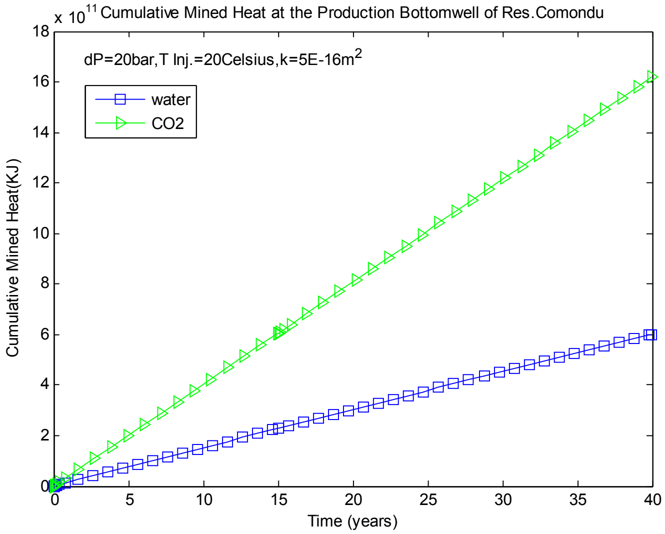


Fig. 7. Simulation results for cumulative mined heat - Comondú.

Mexico), and a low-temperature hydrothermal LER (which are prevalent in the geothermal strip in Baja California). The models for these three representative sites were built with their inherent geophysical-chemical characteristics, but with similar modeling assumptions, geometric parameters and injection/production pressure conditions. From Table 4, it can be seen than the CO_2-based systems have a better heat mining potential than the H_2O-based systems. This is due to the larger sCO_2 mobility at the characteristic temperatures of these geological resources, which helps achieve heat mining rates of approximately 45.8 vs. 42.7 MW, 6.6 vs. 4.8 MW and 1.3 vs. 0.5 MW for the HDR, DSA and LER reservoir, respectively. This also represents enhanced cumulative mined heat of the CO_2-based system with respect to the H_2O-based system of approximately 15, 40 and 170 percent for the HDR, DSA and LER resources.

Additionally, the CO_2 sequestration potential of the HDR, DSA and LER resources are approximately 3.64, 1.66 and 0.42 million tons, respectively, over the estimated 40-years life of the sites. These estimates are based on a reservoir volume equivalent to an area of 1 km^2 area and 500 m reservoir thickness, and a “loss” of CO_2, which is not recoverable of 7 percent. This number has been proposed in Ref. [12] for naturally permeable sites, where non-recoverable CO_2 is considered permanently stored within the geological formation. Reference [6] utilized a value of 5 percent for fluid loss for EGS systems. Scaling up to the actual volume of the respective sites (10 km^3 for Acoculco, 7.5 km^3 for Puruándiro and 2.2 km^3 for Comondú), the annual CO_2 sequestration potential of these three actual sites is 1.85, 0.62 and 0.05 million tons of CO_2/year. To put this in perspective, a typical coal-fired power unit produces about 1 kg of CO_2 per kWh of electrical energy production. This equates, for a typical 350 MW unit (similar to the units CFE owns at the Plutarco Elias Calle - Petacalco Power Station), to approximately 2.34 million tons of CO_2/year/unit (assuming a 0.8 capacity factor). CFE reported that the entire Petacalco Station (seven units) emitted in 2004 about 8.2 million tons of CO_2. Thus, the calculations performed in this study estimate that for a typical most common hydrothermal DSA geothermal resource in Mexico, it would be able to sequester the equivalent of about 25 percent of the CO_2 generated by a typical coal-fired unit in Mexico. This is in addition to the geothermal energy that can be extracted with sCO_2, and avoidance of fresh water usage. It is worthy to mention that previous figures agree well with other research works that were conducted using similar characteristics as the ones used in this work, giving confidence to the assumptions and modeling procedure employed in the work reported in this paper [13,14].

4.5. *Sensitivity analysis*

The process of mining geothermal energy is complex, involving a large number of variables the affect the physical phenomenon. However, according to the literature, the most influencing variables are permeability, porosity, and the distance between injection and extraction wells [6,11]. Therefore, a sensitivity analysis was performed for the HDR, DSA and LER reservoir in terms of the impact driving pressure differential between injection and production wells, injection temperature, fracture permeability and fracture distance have on mined heat extraction rate.

All cases were run with pure sCO_2. For the differential pressure, values of 10, 20, 30 and 40 bar were used; for the injection temperature, values of 20, 30, 40 and 50 °C were used; for the

Table 4
Geological statistics of simulation results for three typical HDR, SDA and LER sites in Mexico (40 years estimates).

Parameter	HDR – Acoculco		DSA – Puruándiro		LER – Comondú	
	CO_2	H_2O	CO_2	H_2O	CO_2	H_2O
Total Heat Mined (E12*kJ)	58.63	50.07	8.34	5.95	1.67	0.61
Average Heat Mining Rate (MW)	45.76	42.62	6.60	4.76	1.33	0.50
Average Produced Bottomhole Temp. [°C]	260.0	257.8	163.6	165.0	94.5	95.0
Average Bottomhole Temp. Drop [°C/yr]	−0.002	−0.062	−0.050	0.000	−0.022	0.000
Average Flowrate [kg/s]	101.76	41.22	18.77	7.84	4.74	1.57
Total Utilized CO_2 Mass [ktons]	51,996	–	23,718	–	5967.7	–
Estimated Net CO_2 Storage Amount [ktons]	3639.72	–	1660.26	–	417.74	–

permeability, values of 6, 8, 10 and 12 mD were used; and for the fracture spacing, values of 50, 75, 100 and 150 m were used.

Fig. 8 a–f, show the impact of increased differential driving force and fracture permeability on heat production from the different reservoirs. The differential pressure can increase the mined heat by as much as a factor of 4.5, when the differential pressure is increased from 10 to 40 bar. Fracture permeability, as expected, is a first order variable, since increased values of permeability increase the ability of the fractures to allow the heat mining fluid to pass through the reservoir, with the heat mining rate doubling for double the value of fracture permeability. The impact of injection temperature and fracture spacing was also found to be of second order.

The pressure sensitivity results were consistent in that the heat extraction increases as the pressure differential increases. For injection temperature, values of 20, 30, 40 and 50 °C were used; while for the permeability, values of 1, 2, 3 and 4 mD were used. The impact of injection temperature was found to be more relevant than for the case of the HDR reservoir, with lower injection temperature providing addition heat extraction. The impact of media permeability on heat extraction was found to be of first order, amounting to about a factor of 4.5 increase in MWs for the permeability used in the sensitivity analysis (see Fig. 8 a–f).

4.6. Estimation of heat mining potential using CO_2

Finally, simulations were individually performed for all of the twenty-one geothermal sites in Mexico with available characterization data. The actual parameters corresponding to each site were used in each model. Twenty of the sites are of the hydrothermal DSA type. The only HDR site in the database was modeled as a fractured site was performed with the TOUGH2 software for a five-spot well configuration consisting of a 1 km^2 area and a thickness of 500 m for each site. Total sCO_2 mined heat, average heat mining rate in MW, sCO_2 flow rate and sCO_2 utilization tonnage was obtained for each site for a period of 30 years (this period was used to be consistent with energy potential estimates provide by Mexican sources). For these simulations a 60 bar pressure differential between injection and production was used, since sensitivity analysis indicated that higher pressure differences provide for higher levels of heat mining. Total recoverable geothermal potential was estimated for each of the sites using the calculation method reported in Ref. [15]. In this method, geothermal potential is estimated using the following equation:

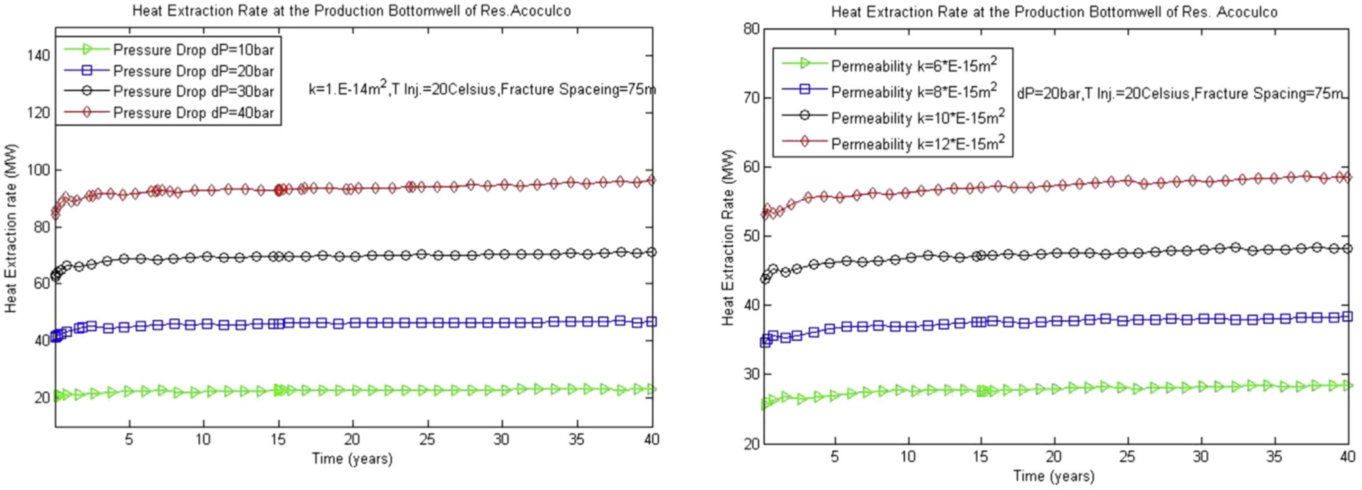
$$Q_{potential} = mnAD[(1-\phi)\rho_{rock}C_{rock} + \phi_{water}\rho_{water}C_{water}]\left(T_{reservoir} - T_{reference}\right) \quad (8)$$

where A is the covering area of the reservoir, D is the thickness of the deposit, and m and n are the ratio of effective covering area to total covering area, and the ratio of effective reservoir thickness to total thickness, respectively. Values in the range from 0.5 to 1.0 are typically used for both, m and n, and values of 0.75 were used in this analysis. Additionally in this equation, Ø is the porosity of the reservoir, ρ represents density, C represents heat capacity and T is temperature. This method applies to hydrothermal sites and it was also used in this study to estimate the heat mining potential for the HDR reservoir, due to the fracturing assumption.

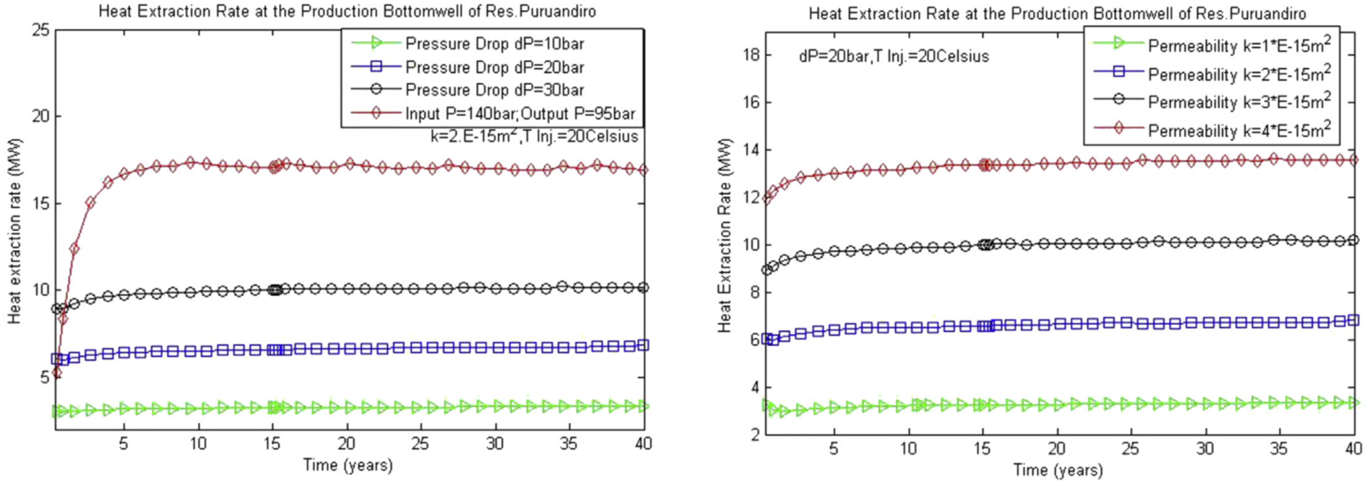
A summary of the simulation results performed for all twenty-one sites is included in Table 5. The range of estimated geothermal heat extraction with sCO_2 for the twenty-one sites expands from 19 MW$_{th}$ for Comondú to 1087 MW$_{th}$ for Graven de Compostela, and 1382 MW$_{th}$ for Acoculco (this, due to the artificially-introduced fractured configuration for the Acoculco site). Estimates of the geothermal recovery coefficient ($R_{geothermal,CO_2}$), with respect to the total geothermal potential, for each site are also included in Table 5. The average value of $R_{geothermal,CO_2}$ is 15.7 percent, with the larger values in the range of 40 percent, corresponding to Maguarichic and San Antonio El Bravo, which have the largest values of permeability of the twenty-one sites, at 4 and 5 mD, respectively. This favors mobility of sCO_2 and enhances its heat extraction from the reservoir. The value of $R_{geothermal,CO_2}$ obtained in this study is within the range of potential values suggested in the literature for geothermal heat recovery by sCO_2. For example Reference [15] suggests a value of 13 percent for CO_2-DSA reservoirs and cites other studies that suggest values for $R_{geothermal,CO_2}$ in the range from 2 to 40 percent. Estimates of MWe were also calculated using a power plant cycle efficiency of 15 percent. The values of electrical power for the twenty-one sites range from 3 to 207 MWe, adding to a total power generation potential with CO_2 of 1161 MWe. This value compares to the 767 MWe of probable potential estimated by Ref. [16] which is included in Table 5 for the same number of reservoirs. This represents 51.4 percent additional power generation that can be mined by the use of sCO_2 on those twenty-one sites. The average ratio of potential power generation by sCO_2 to water is 2.6.

It should be noticed that the calculations indicate that not all the sites offer advantageous conditions for extraction of heat with sCO_2, in relation to the conventional extraction of trapped water (see in Table 5, six sites with a MW-CO_2/MW-CFE ratio of less than 1.0). This is related to the particular conditions and characteristics of the different sites and, perhaps, the accuracy of the probable power generation potential estimates provided in the references. If this CO_2-enhanced heat mining capability were expanded to include the 1380 probable geothermal manifestations in Mexico, with a probable (2P) power generation potential with water of 2077 MWe [18,19], the CO_2-geothermal concept would produce approximately 5400 MWe of electric power, or 12 percent of the 45,000 MWe of additional generating capacity required by Mexico over the next 15 years. An additional estimation that can be made from Table 5 is the amount of CO_2 that could be sequestered by using CO_2 in these

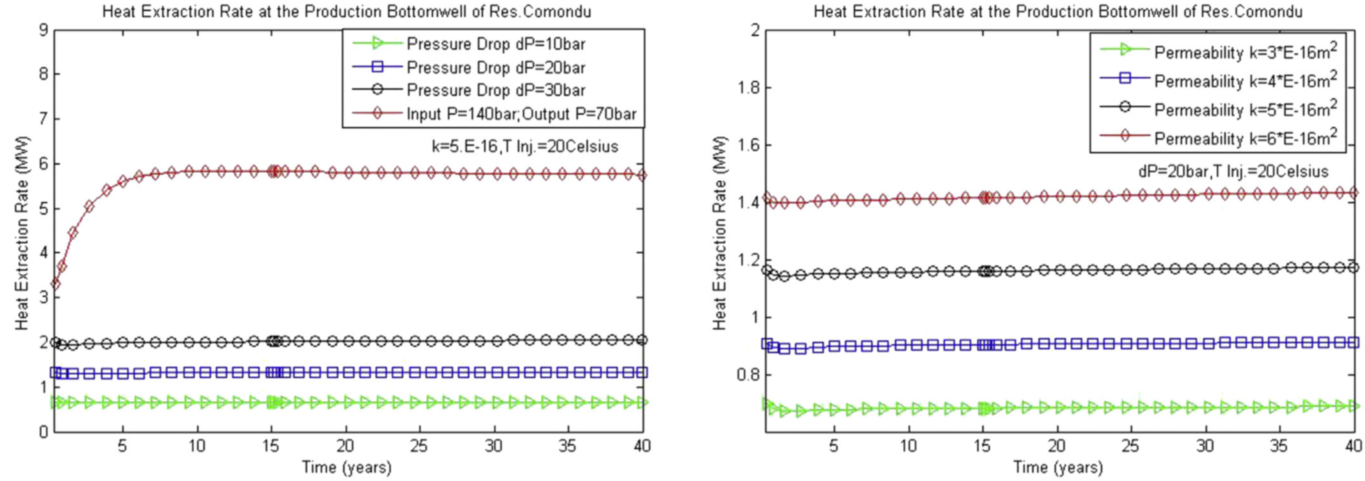
Driving Pressure Differential Permeability



a) HDR– Acoculco b) HDR – Acoculco



c) DSA – Puruándiro d) DSA – Puruándiro



e) LER – Comondú f) LER – Comondú

Fig. 8. Sensitivity Analysis Simulation Results for HDR, DSA and LER reservoir.

Table 5

Summary of Results of Mexican Geothermal Sites Using sCO_2 Heat Mining.

Reservoirs	Total CO_2 mined heat [E12*kJ]	Average CO_2 heat mining rate [MW]	Average produced bottomhole temp. [°C]	Total utilized CO_2 mass [E10*kg]	Average CO_2 flow rate [kg/s]	Calculated geothermal potential with CO_2 [MWth]	Geothermal recovery factor with CO_2 [%]	Estimated geothermal potential, CO_2 [MWe]	Estimated geothermal potential, CFE [MWe]	Ratio MWe CO_2/MWe CFE [-]
La Soledad	20.007	20.836	205.372	4.955	51.531	813	14.9	122	52	2.34
Las Planillas	18.335	19.135	236.239	4.192	43.695	517	12.3	77	70	1.11
Pathé	19.800	20.718	210.297	4.842	50.588	497	14.2	75	33	2.26
Araró	16.941	18.542	212.975	4.107	44.913	267	12.9	40	21	1.91
Acoculco	66.168	69.123	256.681	14.948	155.964	1382	35.3	207	107	1.94
Ixtlán	16.855	18.343	218.143	4.032	43.849	138	12.7	21	17	1.21
Los Negritos	16.937	18.264	218.275	4.050	43.645	219	13.0	33	24	1.37
Volcán Ceboruco	16.435	17.766	238.491	3.731	40.306	355	11.6	53	74	0.72
Graben de Compostela	16.799	18.112	223.386	3.964	42.711	1087	12.2	163	105	1.55
San Antonio El Bravo	43.984	46.594	211.058	10.727	113.483	839	36.5	126	27	4.66
Maguarichic	38.106	40.961	149.192	11.176	119.788	131	45.8	20	1	19.66
Puruandiro	18.508	20.362	161.844	5.191	57.013	305	19.5	46	10	4.58
Volcán Tacana	16.066	17.569	248.615	3.559	38.903	246	10.0	37	60	0.61
Los Borbollones	18.092	19.699	177.762	4.837	52.615	197	14.4	30	11	2.69
Santa Cruz de Atistique	8.663	9.798	183.310	2.278	25.746	100	8.3	15	12	1.25
Volcán Chichonal	16.046	17.551	248.674	3.554	38.856	211	9.8	32	46	0.69
Hervores de la Vega	16.771	18.215	218.642	4.006	43.481	219	9.6	33	45	0.73
Hervores El Molote	2.488	2.836	199.653	0.624	7.109	57	2.0	9	36	0.24
San Bartolomé de los Baños	12.556	13.690	218.635	2.999	32.681	55	9.4	8	7	1.17
Santiago Papasquiaro	13.725	15.136	167.922	3.775	41.585	91	12.3	14	4	3.41
Agua Caliente Comondú	4.144	4.374	91.378	1.390	14.667	19	12.2	3	5	0.57

twenty-one geothermal reservoirs. Based on the computed average CO_2 mass flow rates for each site, the total accumulated mass of CO_2 over the 30-year life of the reservoir, and a 7 percent not-recoverable CO_2 loss, the estimated added CO_2 sequestration potential of these sites for a 30-year operation is of approximately 72 million tons of CO_2 (about 10 percent of the total CO_2 emissions inventory for the country).

5. Conclusions

A study was conducted to assess the feasibility of using supercritical carbon dioxide (sCO_2) injection for heat mining from geothermal reservoirs in Mexico. CO_2 would be available in the future from carbon capture systems added to fossil-fired power plants for greenhouse gases abatement. Traditional water-based geothermal systems require significant amounts of water, a high permeability and porous formation and sufficiently high subsurface temperatures. Supercritical CO_2 is recognized to have good mobility and flow properties that make it an excellent alternative to water for heat recovery from geothermal reservoirs, thus expanding the range of usable natural geothermal formations. CO_2 as a geothermal heat mining fluid also provides the added benefit of carbon capture capabilities within the geothermal formation.

The results of this study confirm the merit of CO_2-based geothermal systems for larger heat extraction rates compared to water-based systems. The following conclusions are made from the results of the study:

- The current installed geothermal power generation capacity in Mexico makes use of hydrothermal resources of high temperature (>200 °C). Four high-enthalpy sites are currently under commercial ownership and production by the CFE (Federal Commission of Electricity) in Mexico. These sites are Cerro Prieto in Baja California with 720 MWe, Los Azufres in Michoacán with 188 MWe, Los Humeros in the State of Puebla with 35 MWe, and the most recent plant of Las Tres Vírgenes in Baja California Sur with 10 MWe. Additionally, the most recent compilation of data on the geothermal potential in Mexico, by the Office of Geothermal Projects of CFE, indicates that there is an additional inventory of 1380 hydrothermal manifestations of high- mid- and low-enthalpy, with total probable reserves of 2077 MWe, by using steam as a heat mining fluid.
- Supercritical CO_2 has better mobility and heat mining ability than water, making it suitable as an efficient alternative for heat recovery from geothermal reservoirs. Simulations using the TOUGH2 computer software, for three typical reservoirs in Mexico (Hard Dry Rock, HDR – Acoculco (260 °C, 160 bar), Deep Saline Aquifer, DSA – Puruándiro (165 °C, 100 bar), and Low Enthalpy Reservoir, LER - Agua Caliente Comondú (95 °C, 75 bar) indicate that driving extraction pressure and site permeability are the first order parameters affecting the heat mining capacity of CO_2. Increasing the driving pressure differential between injection and production wells from 10 to 30 bar enhances the heat mining ability of sCO_2 by approximately a factor of four for all sites. Additionally, it was found that site permeability (or fracture permeability) directly enhances the sCO_2 heat mining ability by the same proportion of the increase in unit permeability, in mD.
- Simulations using the TOUGH2 computer software also show that for the three HDR, DSA and LER sample reservoirs, CO_2-based systems have better heat mining potential than H_2O-based systems, corresponding to enhanced heat extraction rates of approximately 7, 38 and 160 percent with respect to the H_2O-based systems, respectively. It was found that the heat mining capability with sCO_2 increases in inverse proportion to the site subsurface temperature. This suggest that sCO_2 could provide a viable option to exploit the geothermal potential in Mexico.
- Simulations of twenty-one characterized geothermal sites in Mexico, using the TOUGH2 code, estimate heat extraction rates with sCO_2 ranging from 3 to 207 MWe, adding to a total power generation potential with sCO_2 of 1161 MWe. This value compares to a total of 767 MWe of probable potential estimated by Mexican sources for the same number of reservoirs. This represents 51.4 percent additional power generation that can be mined by the use of sCO_2 on those twenty-one sites. If this CO_2-enhanced heat mining capability were expanded to include the 1380 probable geothermal manifestations in Mexico, with a probable power generation potential with steam of 2077 MWe, the CO_2-geothermal concept would produce approximately 5400 MWe of electric power, or 12 percent of the 45,000 MWe of additional generating capacity required by Mexico over the next 15 years. Additionally, a sCO_2-based geothermal system would be able to sequester in these twenty-one geothermal reservoirs, over a 30-year life of the reservoir, approximately 72 million tons of CO_2, or about 10 percent of the current total CO_2 emissions inventory for the country.

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