

Geothermal energy as a means to decarbonize the energy mix of megacities

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The global number of megacities is projected to increase from 33 to 43 by 2030. Megacities are critical for the world's economy; however, their resource management is particularly challenging. The increase of energy demand, in parallel to population growth and climate change, requires urgent investment in sustainable energies. We examine the megacities of Bogotá, Los Angeles, and Jakarta and reveal that the potential geothermal resource base is enough to cover the residential electricity demand by 1.14, 4.25, 1.84 times, respectively. Geothermal energy, a clean baseload resource independent from weather conditions, could significantly contribute to energy needs, improved air quality, and the decarbonization of the world's megacities. We conclude that it is critical that governments and public are educated about the benefits of geothermal. Moreover, those energy policies coupled with investment in research and development are needed to ensure geothermal is successfully integrated into the future energy mix.

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2007 was the year when, for the first time in human history, the percentage of people living in cities exceeded that of people living in the country¹. The increasing population in urban areas determined the escalation of megacities (population of >10 million). There are 33 megacities worldwide, but it is estimated that this number will rise to 43 by 2030² (Fig. 1). Today, >50% of the world's population lives in urban areas, which is forecast to increase to 68% by 2050. The associated greenhouse gas emissions (GHG) will grow from 70 to 80% of the world's GHG discharges in 2050³.

Urban centres account for 67–76% of global final energy consumption, of which an estimated 71–76% is fossil fuel derived⁴. By 2050 the energy growth for heating and cooling of buildings could increase between 7 and 40% based on 2010 statistics⁵. The Urban Heat Island (UHI), effects within mega-urban cities⁶ will magnify the issues associated with global warming⁷. Importantly, megacities today generate about 20% of the world's Gross Domestic Product (GDP). Megacities worldwide face six common challenges: transportation, electricity, water, waste, sanitation, and security. Therefore, it is clear the importance of megacities, especially in light of environmental challenges and climate change on a global scale. Dealing with these challenges requires careful planning and optimization of economic resources.

Both energy demand and consumption will increase in parallel to population growth making electricity and the decarbonization of heating and cooling needs, and the air quality are some of the most challenging issues to deal with for the future of megacities.

Most megacities are distributed in less developed regions, and many of these low GDP regions are experiencing dramatic economic growth (Table 1). It is imperative therefore that sustainability and energy resilience is part of the development strategies for megacities. Despite the technological advancement, the use of sustainable, and greener forms of energy are underdeveloped⁸. There are comparative assessments of peak and annual electric cooling and heating electricity usage at the city-scale, including OECD (Organization for Economic Co-operation and Development) and non-OECD member cities⁹. They propose that OECD cities show a cooling electricity response of 35–90 W/°C/capita above room temperature for cooling. In tropical/subtropical cities outside the OECD suggest that current demand reaches 2–9 W/°C/capita, indicating significant growth in temperature-dependent electricity demand as air conditioning is adopted. A similar situation is observed on the heating process, with subtropical cities adopting electric heaters, increasing electricity generation and delivery concerns.

While renewable energies like wind and solar are considered potential suppliers for megacities and are highly cost-effective sources for electricity, they are also related to some technical problems. For instance, wind turbines can be noisy, occasionally impact the physical environment, are aesthetically an eyesore, and are weather dependent. Solar panels, unless installed on the roof of buildings, require considerable space. Solar panel parks not only require re-purposing of land and potential destruction of forests, but they can also change the surrounding soil's temperature with consequences in some ecosystems. In contrast,

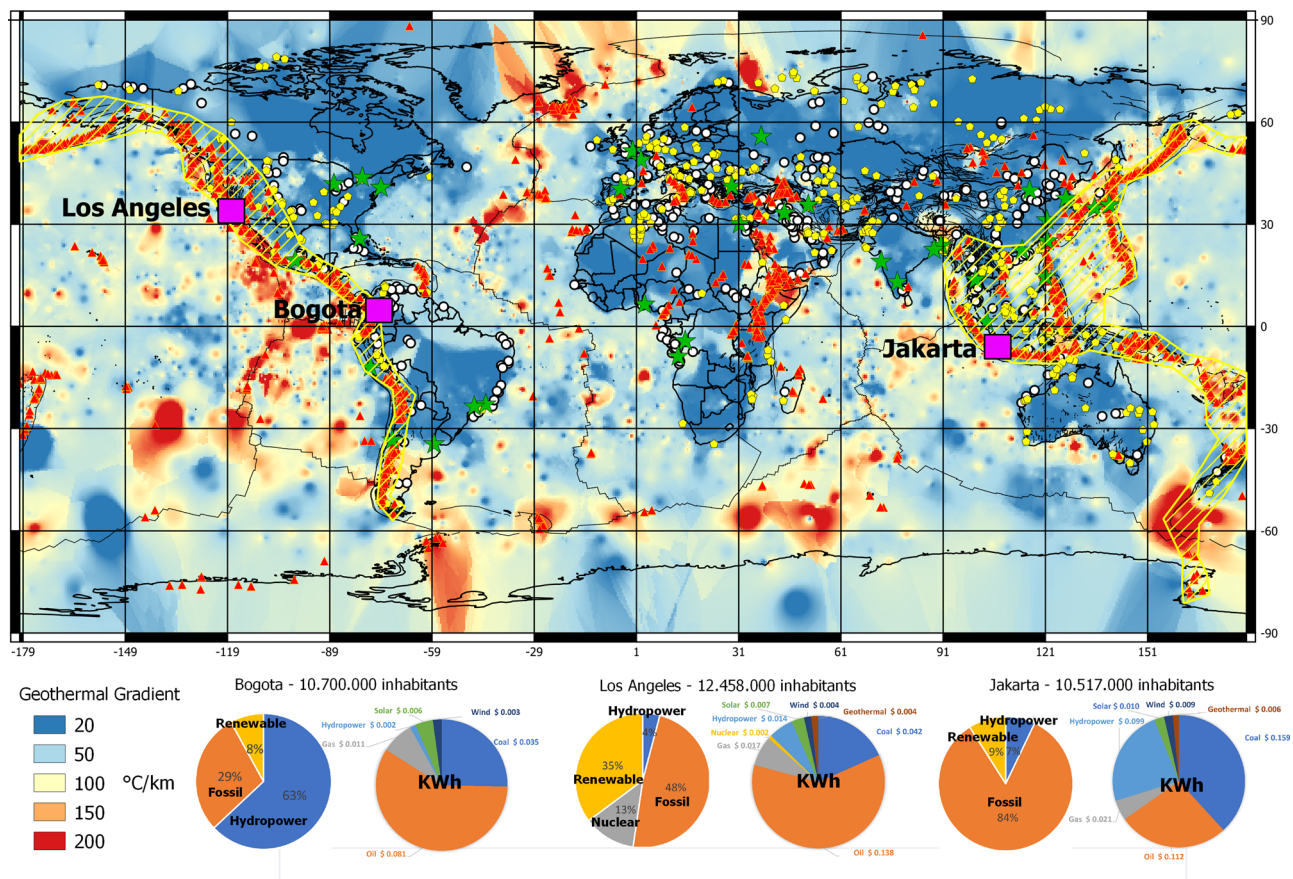


Fig. 1 Worldwide distribution of geothermal gradient anomalies. Locations of volcanic belts (red triangles) and hydrocarbons occurrences (white circles correspond to oil fields and yellow pentagons correspond to gas fields) have been combined with distribution of megacities (green stars). The ring of fire is presented as the yellow hatched polygon. Statistics of participation of energy production technologies are shown in the lower panel (left pies), as well as costs of energy production of one kWh (right pies) for Bogotá, Los Angeles, and Jakarta cities (purple squares on the map). Coordinate system in WGS-84.

Table 1 Population, urbanized area, and heating and cooling degree days of world's largest cities.

World's largest cities (1)		Population in 2018 (thousands) (2)	Urbanized area in km ²	Heating degree days °C*d/yr ¹	Cooling degree days °C*d/yr ²
Tokyo	Japan	37,468	13,100	1594	227
Delhi	India	28,514	1114	396	1174
Shanghai	China	25,582	1600	1664	370
Sao Paulo	Brazil	21,650	1958	495	120
Mexico City	Mexico	21,581	793	837	45
Cairo	Egypt	20,076	1574	440	574
Mumbai	India	19,980	4350	1	1216
Beijing	China	19,618	3377	2955	218
Dhaka	Bangladesh	19,578	911	50	1164
Osaka	Japan	19,281	1138	1728	311
New York	USA	18,819	10,768	2318	133
Karachi	Pakistan	15,400	2000	153	1149
Buenos Aires	Argentina	14,967	3209	199	1174
Istanbul	Turkey	14,751	5343	1996	123
Kolkata	India	14,681	185	96	1076
Bangkok	Thailand	14,600	2944	NA	NA
Manila	Philippines	13,482	636	0	1027
Lagos	Nigeria	13,463	999	0	1012
Rio de Janeiro	Brazil	13,293	1084	37	385
Guangzhou	China	12,638	4050	539	725
Los Angeles	USA	12,458	12,562	887	7
Moscow	Russia	12,410	737	4562	50
Shenzhen	China	11,908	1991	377	685
Lima	Peru	11,400	136	NA	NA
Paris	France	10,901	2535	2157	24
Bogota	Colombia	10,700	397	NA	NA
Jakarta	Indonesia	10,517	556	1	976
Seoul	South Korea	9963	363	2,870	59
London	UK	9046	560	2333	6
Tehran	Iran	8896	1390	1977	708

Data for population are taken from UN², and for urbanized area, heating and cooling degree days for 2018 are taken from the Global Residence Index (<https://globalresidenceindex.com/hnwi-index/climate-index/>). 1 Heating degree days (HDD) are defined to a base temperature (which depends on the building standards), below which a building needs heating. An HDD is counted for every degree in which the mean daily temperature is below the base temperature (18.33 °C). 2 Cooling degree days are defined to a base temperature, above which a building needs cooling. A cooling degree day is counted for every degree in which the mean daily temperature is above the base temperature (18 °C). For locations, like Osaka, we used the website <http://www.degreedays.net> to calculate a 2018-year average of heating and cooling degree days using data from the airport weather station.

geothermal energy is rarely considered despite several megacities worldwide are located in regions with anomalously high geothermal gradient, especially around the ring of fire, a plate boundary zone with high tectonic and volcanic activity that surrounds the Pacific Ocean (Fig. 1). The benefits geothermal brings over wind and solar are that it is baseload, meaning it is available 24/day, it is not dependent on any day/night cycles and weather conditions thus, it has a high-capacity factor, bringing stability to the grid, and importantly, it requires a small land footprint^{10,11}. Electricity derived from geothermal developments may be able not only to meet the increase energy requirements of megacities but also contribute to the future energy demands. In addition to the residential sector, there are also other industry applications that can use heat from geothermal circuits, such as agriculture in greenhouses, food preservation, textile industry, etc.

Geothermal energy for power production today can be applied using conventional, high, and low-temperature hydrothermal systems. Moreover, there are several ongoing research programs examining the possibility of supercritical geothermal systems, which significantly increase the power density^{10,11}. Engineered concepts such as Enhanced Geothermal Systems (EGS), where the rock is fractured to increase the natural permeability extend the geothermal play potential. Furthermore, emerging Advanced (closed-loop) Geothermal Systems (AGS) as they are often called^{10,11}, potentially open the concept of geothermal heat and power to an even wider geographic application. Geothermal energy use, particularly EGS, where fractures are introduced into

the subsurface are often sighted as causing induced earthquakes. Studies past and present are designed to mitigate these concerns through detailed pre-drilling research, including stress field analysis and modelling^{12–14}, in addition, projects require increased public relationship building and education^{15–18}.

According to Ourworldindata¹⁹, Colombia is a net energy exporter with ~2.5 times its total consumption in 2019 sent outside the country (535 TWh, of which low-carbon sources represent ~68.58%). Recently, USA has become a net exporter of energy, largely due to success in its fracking industry, which supports the domestic delivery of ~100% energy of its consumption (26,291 TWh, of which low-carbon sources represent ~39.95%), and excess to other countries. In contrast, Indonesia has become a marginal importer with ~9.21% of its consumption (2475 TWh, of which low-carbon sources is ~16.95%). The three countries presented as examples in this paper are signatories of the Paris Climate Change Agreement with challenging targets to reduce greenhouse gas emissions by 2030 and promise accelerated sustainable and resilient development^{20,21}. The treaty outlines a target reduction of emissions below the 2005 baseline, which means a decrease of 51% for Colombia: 50% for the USA, and 41% for Indonesia. These reductions are mainly based on strategies of energy efficiency, incorporation of renewable energy, waste reduction, increasing fuel efficiency in transportation and logistics, etc.

Energy demand from megacities varies according to the level of development. Indicators used to evaluate the relationship between

the energy use by a country and its level of development are controversial²²; however, a suitable variable is the energy consumed worldwide to produce the goods and services demanded by that country, i.e., its energy footprint. Thereby, megacities as strategic places where goods are produced or delivered, become intimately related with the level of development of countries that host them. Megacities in Northern America, Europe, and Japan use on average, per capita, more than 60 GJ (16.6 MWh)—and up to 100 GJ (27.7 MWh) e.g., Los Angeles and New York²³. In some megacities, new initiatives to improve air-quality through the increased use of electric vehicles may also challenge demand on electrification.

This study was inspired by initiatives, such as the Green Deal Agreement, which highlight the need for climate neutrality by 2050²⁴. We investigate the geothermal potential in Bogotá (Colombia) and follow the same workflow with Los Angeles (California) and Jakarta (Indonesia) as case studies. From the geothermal resource potential, we calculate a geothermal resource base (GRB)/energy consumption ratio. This concept could, however, be easily applied to any other megacity in the world. In addition, based on current and future energy statistics, we consider the decarbonization potential of geothermal for the three cities studied. Finally, we argue that the adoption of governmental incentives, regulation and a planned framework for decarbonizing power systems through renewable energy technologies, in particular the use of geothermal energy, could provide an important contribution to the energy demand, decarbonization, and air-quality improvement of megacities today and in the future, improving the quality of life for many people and helping to reduce energy poverty.

Energy demand of megacities. Analysis reveals that the energy demand in many megacities around the world is often below 20 GJ (5.5 MWh), largely because two-thirds of the megacities are in regions with warm climate (37% in the subtropics, 37% in the tropics, and 26% in the temperate zone; Table 2). In temperate climates, there is an increase in energy demand in cold months for heating. Most cities require cooling, with the energy for air conditioning being largely derived from electricity, hence depending on the available capacity of power generation and the existing grid. The implications of global warming combined with seasonal variations and the UHI effect may lead to power shortages if infrastructure/planning is not updated. The impact of the UHI alone reveals that temperatures today in cities can be an estimated 0.5–4 °C above unpopulated areas⁶. Simple analysis, presented in supplementary tables, suggests that the impact of an average 1.5 and 3.0 °C temperature increase, is a gross increase in power use principally required for cooling, resulting in an estimated 14 and 22% increase in energy. Megacities in a global warming scenario could see a dramatic increase in cooling needs, which poses a problem regarding the planning of new construction and retrofiting. Future buildings may need to be constructed to keep the heat out, rather than in.

In addition to energy demands, climate change may be putting strain on the water supply. Megacities located in the subtropics might experience lower than average precipitation as weather patterns change. Water resources could be impacted requiring access to future water supplies from desalination or recycling of wastewater, all of which increases the future energy demand. At least 19 of the 30 megacities included in Table 1 obtain more than one-third of the water supply from both surrounding areas and surface waters²⁵.

When we look at the selected cities for this study, Bogotá, Jakarta, and Los Angeles, it is seen that the challenge of decarbonizing the energy for each city is strikingly different, as

Table 2 Average energy parameters in megacities, from 2001 to 2011²³.

Energy parameters in megacities	Average	Perc. Standard deviation [%]
Inhabitants	15,183,543	38.33
Heating degree days ¹	1136	98.81
Cooling degree days ²	546	85.33
Total energy demand [GWh]	240,577	81.32
Electricity	56,837	91.43
Heat (incl. industry)	119,930	82.05
Transport	63,809	102.79
Water consumption [Mm ³]	2607	101.44
Solid waste [kt]	5637	107.27

is the present-day per-capita energy consumption for each city (Table 3). The issue of decarbonization is biggest for Los Angeles, whereas the projected energy needs for Jakarta and Bogotá, as these societies modernize their economies, presents a challenge of balancing improved lifestyle expectations and future decarbonization of the energy infrastructure. One common aspect that all these megacities exhibit is that they each face a decarbonization challenge, yet they all sit on a potential geothermal resource that is not currently utilized.

With respect to the geological setting for Bogotá, Jakarta, and Los Angeles, we find that all megacities are located close to subduction-related plate boundaries (Fig. 1). While this is not a unique to geothermal potential, it is a common theme of the megacities presented in this study. Furthermore, it is observed that geologically speaking, each region has experienced recent volcanic activity and crustal magmatic intrusions which enhance the potential of present-day geothermal anomalies for these megacities. The megacities Bogotá and Los Angeles are both located along Pacific Ring of Fire, where the Pacific plate is subducting under the Americas; however, locally they exhibit distinct geological characteristics (Figs. 1–3). Jakarta, by comparison, is located on the island of Java, which is identified as an active volcanic island arc in the Indonesian archipelago at the southern margin of the Eurasian plate (Figs. 1, 4). Supplementary Note 1 contains an extended review of each megacity its current energy use, energy mix and a summary of the unique geological setting for each region.

Results

The GRB potential is computed for each region following recognized methodologies^{26,27}. We calculated for each region the maximum value of recoverable resource within a delineated area. Then, we simplified the model and hypothesize, firstly, that the tectonic features control the location of hot spring-waters and secondly, that the area encompassing the springs can be used to define the area and volume of potential reservoir that is storing the thermal energy.

Bogotá. Bogotá is in the Eastern Cordillera Basin (Fig. 2). Here a maximum value of recoverable resource is calculated within an area of ca. 7500 km², at an average depth of 3 km, from a 30 m thick sandstone reservoir (the Eastern Cordillera Basin is approximately 11 km deep, and hosts at least one regional reservoir unit, the Une Formation²⁸). Our estimations suggest a rough value of resource of approx. 16,603.1 GWh, (Fig. 2), corresponding to ~1.14 times the energy per capital consumed by all people located in the metropolitan area. That means geothermal power could potentially cover the total residential power demand for Bogotá. This amount of energy may guarantee enough resources for long-term geothermal plants that take advantage of

Table 3 Main volumetric parameters used for estimating the energy and information about the total energy per capita consumed by all inhabitants for these megacities.

N	Area km ²	Thickness (m)	Φ	ρ _r kg/m ³	C _r J/ kg°K	C _w J/ kg°K	ρ _w kg/ m ³	ΔT (°C)	GWh estimated	Est. Population	kWh Per Capita	Consumption all people GWh
Bogotá	7500	30	0.05	2800	920	4189	1000	100	16,603.1	10,700,000	1355.8	14,509,200
Los Angeles	9400	450	0.05	2800	920	4189	1000	100	312,138.8	12,458,000	5900	73,502,200
Jakarta	9100	30	0.05	2800	920	4189	1000	100	20,145.1	10,517,000	1039	10,927,163

its location for supply electricity, and hot waters for industrial and recreational processes.

Los Angeles. Using the same assumptions for Los Angeles, which is located in the Los Angeles Basin (LAB) it is observed that spring-water occurrences cover an area of approx. 9.400 km². This area coincides with relatively surficial Curie Point Depth (CPDs), ranging between 15 and 25 km. Having into account this figure, we have followed same approach to estimate the maximum recoverable resource, using formula (1) and assuming an average depth of 3 km, one 450 m thick reservoir related to the main grauwacke or McLaughlin's Unit ²⁹. In this case, it is used half of the thickness than in NW Geysers Geothermal Field area³⁰. Our estimations suggest a rough value of resource of approx. 312,138.8 GWh, corresponding to approx. 4.25 times the energy per capita consumed by all inhabitants that live in this megacity (Fig. 3).

Jakarta. Although the CPDs in the area are <25 km, the distribution of volcanic cones and spring-water occurrences were taken as criteria for defining the main area for focusing a detailed geothermal exploration near to Jakarta city. The ellipse envelope that encompasses them defines an area of approx. 9.100 km². Using the same approach as in previous cases, we assume an average depth of 1.0 km, one 30 m thick reservoir related to the Loka andesitic pyroclastic unit (using similar thickness from the Wayang Windu geothermal field, West Java³¹). The estimations indicate a rough value of resource of approx. 20,145.1 GWh, corresponding to 1.84 times the energy per capita consumed by all people that are currently living in this megacity (Fig. 4). Table 3 summarizes the main volumetric parameters used for estimating the energy and information about the total energy per capita consumed by all inhabitants for these megacities.

Discussion geothermal and megacities: How can geothermal help megacities?

Advances in Conventional, EGS and AGS, facilitate the concept of producing, low-carbon, sustainable, electricity, and heating adjacent to large population centres. In addition, low-grade heat may be used directly in district heating/cooling and Ground Source Heat Pumps, can be retrofitted, and developed in new building developments further decarbonizing heating and cooling needs for office buildings and homes^{10,11}. Medium- and low-enthalpy geothermal energy can be used to decrease both operation costs and environmental impact from a broad range of industries including desalination of water, green houses, fish farming, brewing/fermenting, chemical products, automotive, and large-scale production industry¹⁰. The combined approach of geothermal for heating and cooling and for electricity production, therefore, enables geothermal to decarbonize significant amounts of the energy needs especially if it is developed in conjunction with solar photovoltaics (Solar-PV), wind power, and improved insulation technologies for existing and new office building and homes.

Geothermal and megacities: Prospective, economic, operational risks, and environmental impacts. Early studies have shown that conventional geothermal developments may be associated with the release of gasses such as hydrogen sulfide, carbon dioxide, methane, and ammonia, the amounts of gas released is significantly lower than in the case of fossil fuels. Furthermore, there are ways to mitigate this with the addition of air scrubbers, although it can add to the cost of development. In any subsurface geothermal drilling operation earthquake risks might be associated depending on the state of stress in the earth's crust. This is increased in the case of enhanced geothermal power plants, which force water into the Earth's crust to open fissures to increase the resource potential. However, this activity may be controlled by careful pre-drilling research including natural seismicity monitoring and by adjustments in the rate of water injection. It should be noted, however, that the above environmental concerns can be significantly reduced through AGS, and closed-loop/binary geothermal completions for both heat and power developments¹⁰.

There are relevant risks related to uncertainties of the properties of the geothermal field derived from the prospecting stage, but also in the management of the permeability for liquid extraction or reinjection during the lifetime of the geothermal fields. These issues relate to open-loop developments for example conventional, EGS and low-temperature geothermal completions which utilize the natural brine and host-rock interactions. In managing these power-plants the proper control of pressure and the induced seismicity are frequent concerns related to the management of the permeability that inhibit the development of this sort of renewable resource, particularly in EGS developments. For the appropriate management of a conventional geothermal field, it is essential that the entire liquid produced from geothermal wells is reinjected³². But this issue triggers a major operational challenge because mineral precipitation owing to boiling or cooling in the proximity of a production or reinjection well can result in reducing levels of liquid extraction or fluid injectivity gradually.

There are also significant risks linked with drilling geothermal wells, and their ultimate capacity is often challenging to assess due to large variability of the permeability on the scale of tens to hundreds of metres. Early work done to study the local stress conditions, in order to understand the present-day principal stress directions (Figs. 2–4) and fluid flow, can be used to reduce the economic risk of drilling a dry geothermal well, and significantly the understanding of open fracture orientations can help improve the location of horizontal wells, thus improving flowrates and well productivity. Other risks associated with geothermal wells are related to the influence of drilling in the reservoir, variations in well discharge pressure and temperature following long-term utilization of a geothermal structure, the presence and formation of a non-compressible gas cap, scaling of amorphous minerals, and corrosion. Nevertheless, all those identified risks are frequently taken in account in operational protocols with reduction of their impacts in the surrounding

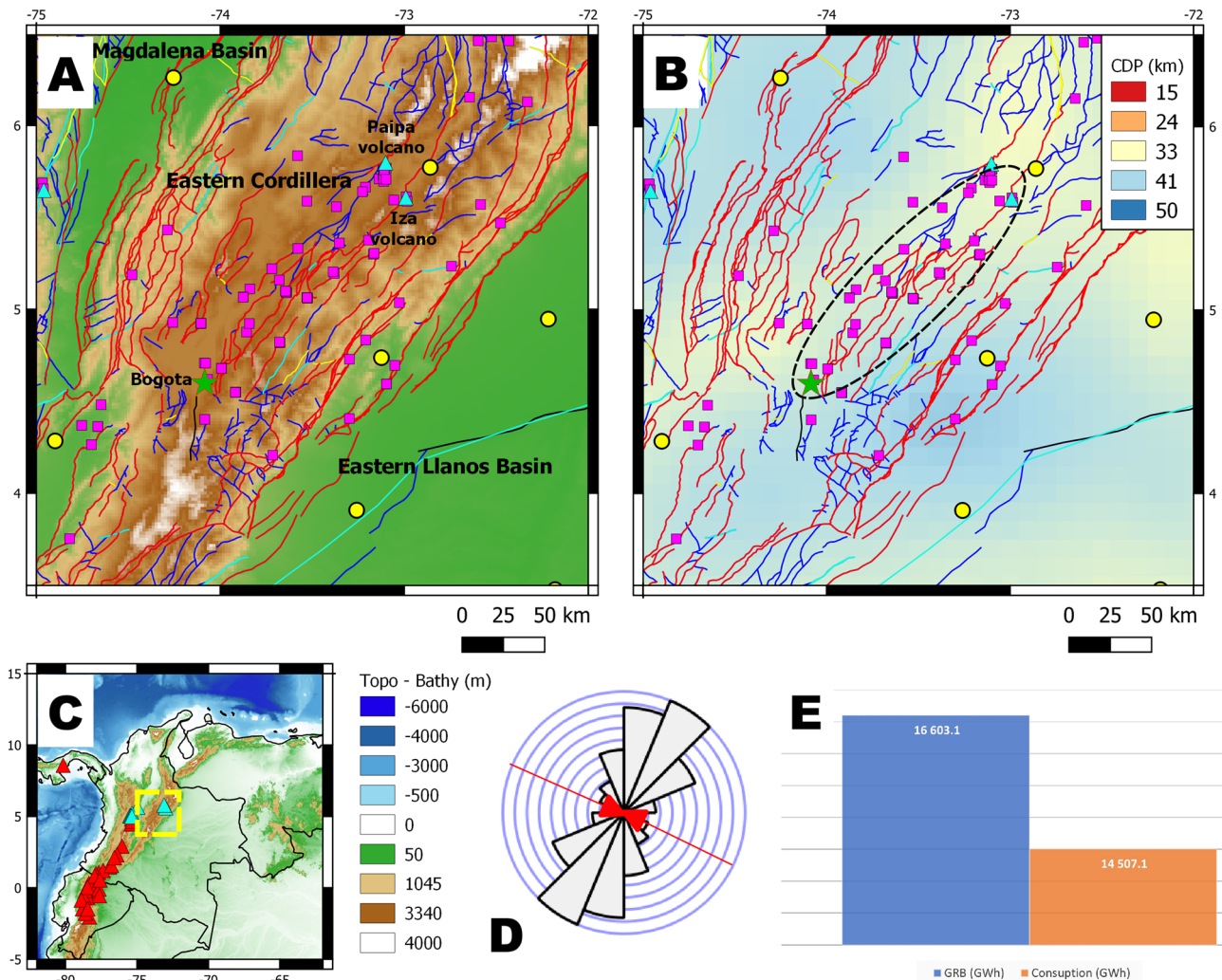


Fig. 2 Geothermal system north of Bogotá. **A** Spring water distribution (purple squares) in the north of Bogotá. **B** Calculation of the Curie Point Depth (CPD) in the area north of Bogotá⁵⁴. Maps display normal faults (blue lines), reversal faults (red lines), right-lateral faults (cyan lines), left-lateral faults (yellow lines), active volcanoes (red triangles), inactive volcanoes (cyan triangles), and O&G fields (yellow dots). Topography from Amante and Eakins⁵⁹. Black-dashed ellipse corresponds to the hypothetical envelope that encompasses the main geothermal lead. **C** Study area in a regional context; **D** rose diagram showing regional fault trending and the maximum principal stress direction (red arrows showing compressive regime); Rose diagrams are expressed in eight intervals of azimuth to the respective length of faulting. **E** Comparison between the potential geothermal power expressed as GRB (estimated in this work) and the current energy consumption in the metropolitan area of Bogotá. Coordinate system in WGS-84.

areas. For instance, the impact of the induced seismicity due to reinjection of fluids is becoming controlled by using traffic light protocols³³.

Geothermal resource administration and regulations. Present external costs for each energy resource in each G20 country suggesting that geothermal energy becomes higher price than other sources³⁴. Thus, in addition to previously identified risks and the current costs of installation and operation, the poor communication and education within local communities regarding the value of regional and local energy resources, potential hazards, and their mitigation or management, may lead to backlash and even social rejection, as well as cause low competitiveness in terms of price due to its low commercial penetration. If the social approach is managed properly, the geothermal resource could provide significant decarbonization of the power needs for megacities, something that promotes greater attractiveness about its use. Besides, geothermal can bring local benefits (e.g., job creation) and reduce the public expense in the energy

sector. GEOENVI (2020)³⁵ recently reported that geothermal has brought an annual saving of 2.6% of GDP to the Icelandic economy.

It is important to note the innovation occurring within the geothermal industry, and new geothermal resources could be utilized by taking advantage of recent advances in geothermal completions utilizing binary, closed-loop, or AGS, which fully mitigate environmental issues common with flash-geothermal power plants^{10,11,36,37}. While binary, closed-loop developments and AGS can increase the cost level of geothermal development, these newer concepts allow a wider deployment of geothermal energy, for power production and provide long-term cost-efficiencies to regions that prioritize GHG reduction targets^{10,11}. These technological developments coupled with positive policy and low-carbon recognition of geothermal technologies, such as in California with the designation that binary/closed-loop technologies are of zero carbon³⁷ could encourage the development of more geothermal developments^{10,11}. AGS developments are particularly interesting because they decouple the need for the co-location of permeability, heat, and fluids in the sub-surface

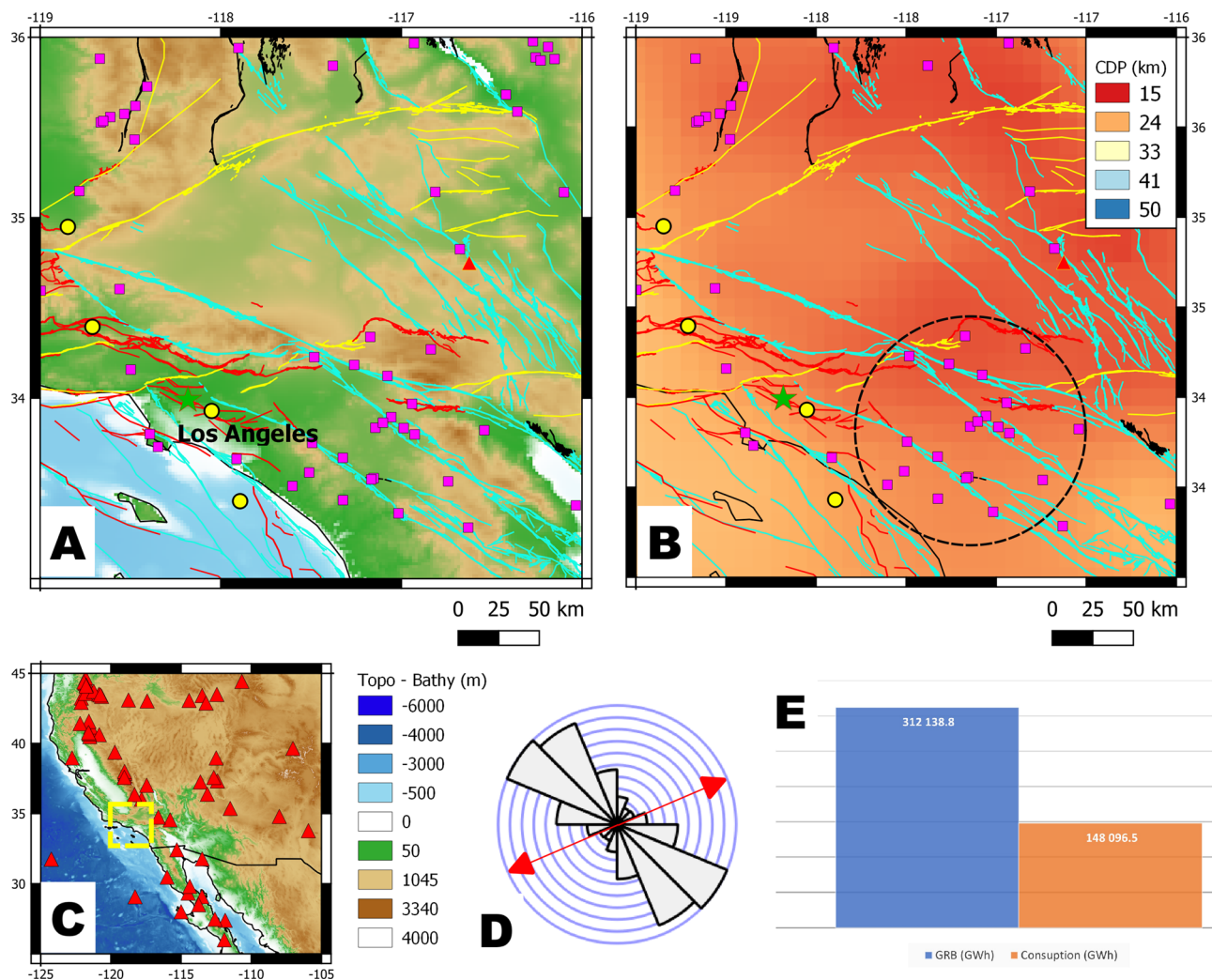


Fig. 3 Geothermal system of Los Angeles. **A** Spring water distribution (purple squares) in the area of Los Angeles. **B** Calculation of the Curie Point Depth (CPD) in the area north of Bogotá⁵⁴. Black-dashed ellipse represents a hypothetical envelope encompassing the main geothermal leads. Maps display normal faults (blue lines), reversal faults (red lines), right-lateral faults (cyan lines), left-lateral faults (yellow lines), active volcanoes (red triangles), and O&G fields (yellow dots). Topography from Amante and Eakins⁵⁹. Black-dashed ellipse corresponds to the hypothetical envelope that encompasses the main geothermal lead. **C** Study area in a regional context; **D** rose diagram showing regional fault trending and the maximum principal stress direction (red arrows showing compressive regime); Rose diagrams are expressed in eight intervals of azimuth to the respective length of faulting. **E** Comparison between the potential geothermal power expressed as GRB (estimated in this work) and the current energy consumption in the metropolitan area of Los Angeles. Coordinate system in WGS-84.

also offering additional flexibility and a possibility to scale (i.e., larger), future, geothermal power plant developments¹⁰.

Penetration of geothermal has been limited due to the low-cost of fossil fuels. However, with the right incentives and forthcoming carbon tax schemes geothermal could appear increasingly attractive. Geothermal provides a low-carbon baseload power, which importantly offers grid stability, meaning it could provide a realistic pathway to the closure of coal and gas power plants^{10,11}. To date, the preference of the, apparently, cheaper wind and solar-PV technologies, unfortunately, lock economies into a carbon-based gas or coal infrastructure³⁸, precisely because wind and Solar-PV lack the baseload component. Geothermal power is also flexible, allowing power plant operators to ramp up and down the resource, therefore making it the perfect low-carbon partner with wind and solar-PV and hydroelectric resources. Given the geotectonic position of several world's megacities, we see a huge potential for the use of geothermal power which would also reduce the environmental impact and help contrasting the energy challenge in overpopulated areas.

Regarding regulation, there are a series of legal issues which are a good guide for the proper regulation of this resource (e.g., royalty payments, use fees, environmental protection, freedom of Information, rights-of-way under the land policy and management, minerals management, leasing, operations, rights of local communities, etc.) that are permanently updated by countries and states that have a developed geothermal industry (see, for example, the USA code of the state and federal regulations³⁹), in the process of development (see, for example, the Law of the Republic of Indonesia No. 21 of 2014 about Geothermal⁴⁰), or that foresee the potential use of this resource in the medium or long term (see, for example, the proposal to modify the Decree 1073 of 2015 of the Ministry of Mines and Energy of Colombia⁴¹).

Geothermal resource decarbonization potential for megacities. Based on the statistics and the per-capita estimates for the power use within the three studied megacities a decarbonization potential for geothermal was calculated for the three different megacities (see Supplementary Table 3). The calculation

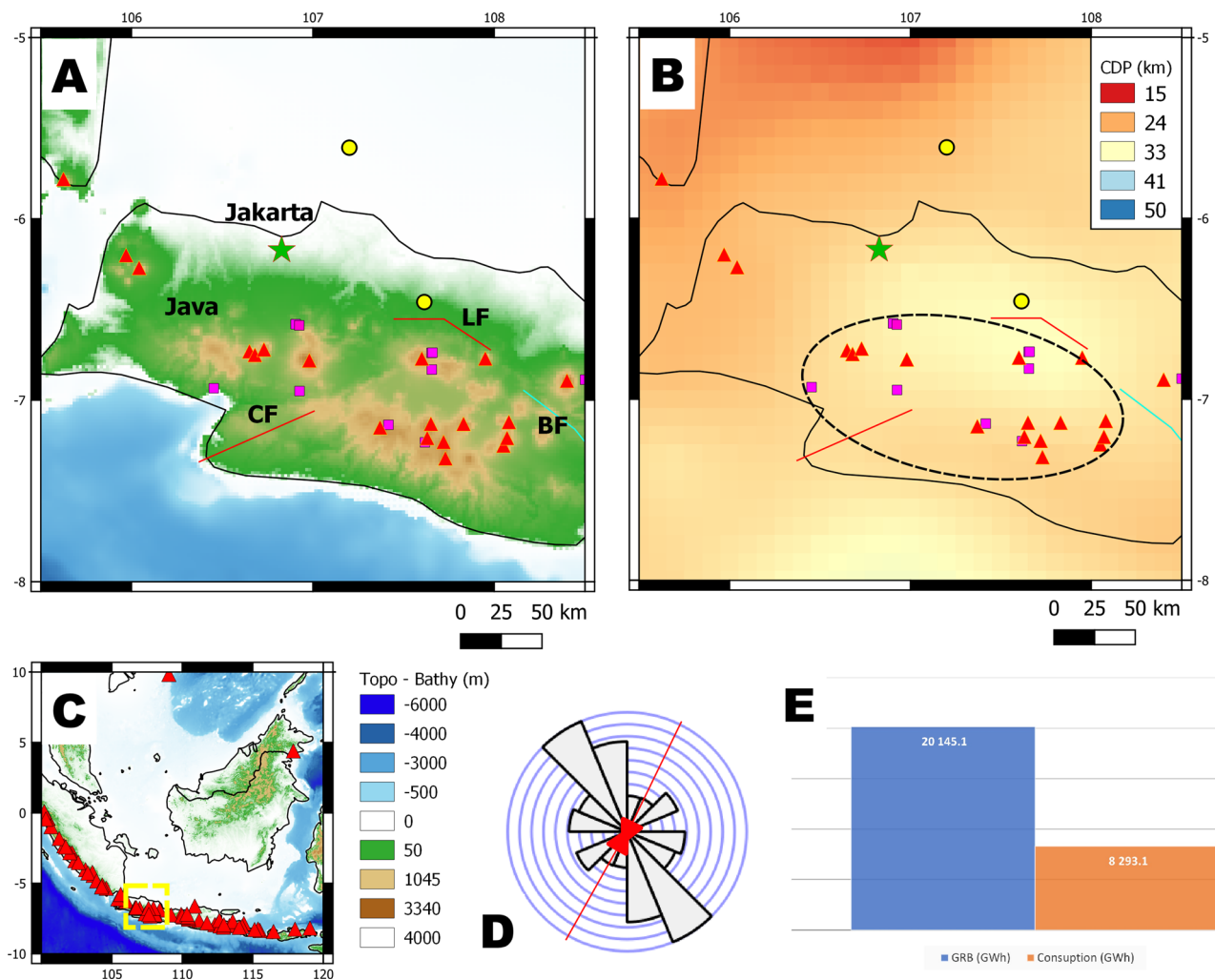


Fig. 4 Geothermal system of Jakarta. **A** Spring water distribution (purple squares) in the area of Jakarta. **B** Calculation of the Curie Point Depth (CPD) in the area north of Bogotá⁵⁴. Black-dashed ellipse represents a hypothetical envelope encompassing the main geothermal leads. Maps display normal faults (blue lines), reversal faults (red lines), right-lateral faults (cyan lines), left-lateral faults (yellow lines), active volcanoes (red triangles), and O&G fields (yellow dots). Topography from Amante and Eakins⁵⁹. Black-dashed ellipse corresponds to the hypothetical envelope that encompasses the main geothermal lead. **C** Study area in a regional context; **D** Rose diagram showing regional fault trending and the maximum principal stress direction (red arrows showing compressive regime); **E** Comparison between the potential geothermal power expressed as GRB (estimated in this work) and the current energy consumption in the metropolitan area of Jakarta. Coordinate system in WGS-84.

considered the amount of carbon emitted by the fossil fuel vs that emitted by the assumed geothermal technology, flash, or closed loop. The difference is the net decarbonization that geothermal can achieve. Supplementary Table 3 highlights the assumed full life emissions assume for the different energy technologies replaced. It was assumed that there was no need to replace existing low-carbon power sources such as wind, solar, hydrothermal, and nuclear. The decarbonization calculation was completed assuming the replacement of biomass, biogas, gas, coal, and oil sources (Supplementary Table 4). In total eight different scenarios were investigated assuming either 100% replacement using flash or closed-loop geothermal technologies (Scenario 1 and 5), assuming a global warming scenario with increased (120%) of present-day energy demand (Scenarios 2 and 6). Each of these scenarios was compared with only a 20% of fossil fuel demand removed by geothermal technologies (Scenarios 3, 4, 7, and 8).

Computing a decarbonization estimate introduces significant assumptions, particularly the penetration that geothermal can

realistically achieve. A key uncertainty in the calculation is the true full-life cycle carbon footprint for different energy technologies. This uncertainty was important in the calculation of emissions in Bogotá where the electric system relies heavily on biomass. Biomass is controversial with respect to its carbon footprint^{42–44}, thus the numbers presented in Supplementary Table 3 and used here could therefore be considered an upper estimate for the city. Assumptions are also derived from the estimates of the power use per capita. Firstly, this only represents the residential sector not the full transport, commercial, or industrial energy use of the megacity. The future energy demand is likely to change significantly for Jakarta and similarly Bogotá which as of today are considerably lower than Los Angeles. In future, changes in life standards and the introduction of electric vehicles will likely increase the residential electric demand on the grid. The values of per-capita and approximate population statistics used in Supplementary Table 3, are derived from the literature and represent some errors inherent in capturing this information accurately. Regardless, the calculation gives us an

idea of the current need and scope for decarbonization. In this study we also considered what the impact of climate change could be on the overall power needs whether that be heating for cooling because of 1.5 °C or 3.0 °C temperature changes (Supplementary Table 1, 2), our simple calculation estimated 14–24% change in these scenarios respectively. To simplify the analysis, we assume a scenario of 20% increased power usage, this might be high for the former scenario and low for the latter scenario, but such a calculation is fraught with error due to population growth forecasts, changes in life quality and expectation and post-covid population changes. Finally, it is probably incorrect to consider that decarbonization could be achieved alone by geothermal, despite our geothermal resource results revealing there is enough geothermal potential to achieve this. It is hard to predict what is a reasonable estimate. Therefore, we begin with a modest estimate of geothermal penetration accounting for 20% of decarbonization for residential power use. By assuming only limited development of the geothermal potential the assumption is that only the best, most cost-effective geothermal projects are completed. One factor that might change the successful penetration of geothermal is the successful demonstration and cost reduction of AGS and supercritical AGS geothermal power plant developments. Today, however, it is clear with the current rate of uptake, geothermal penetration will not occur without the relevant incentives and governmental support.

The results of this simple calculation suggest that if geothermal replaced all fossil fuels in Bogotá geothermal could have a decarbonization potential of 15.4–17.0 MtCO₂e per year. If we assume only 20% substitution of fossil-fuel by geothermal power when decarbonizing in Bogotá (for example only the best geothermal projects) geothermal could only achieve a decarbonization potential of 3.1–3.4 MtCO₂e per year. If future demand is based on global warming this could be as high as 3.7–4.1 MtCO₂e per year based on our calculations and assumptions. For LA the results suggest ranges of 20.9–25.1, MtCO₂e, 4.2–5.0 MtCO₂e, and 5.0–6.0 MtCO₂e per year. In Jakarta, we estimate 6.9–7.9 MtCO₂e, 1.4–1.6 MtCO₂e, and 1.7–1.9 MtCO₂e per year.

The estimates presented here only represent that for conventional and EGS-types of geothermal exploitation, involving heat, porosity, and high-water flow rates. These estimates already highlight that geothermal derived power can be sufficient to decarbonize the present energy needs. The reality is however geothermal might not make the level of penetration without changes in governmental regulation. In some cases, it may also help support and decarbonize the future energy needs resulting from climate change and global warming (Supplementary Tables 1, 2). Importantly, geothermal derived power is not as vulnerable to environmental changes, and, importantly, it provides a low-carbon baseload power. The global share that geothermal power will contribute is 5% of the electricity by 2050⁴⁵. In contrast to wind and solar energy, geothermal energy does not present intermittency, which would be an advantage in megacities. In fact, expanding massively its use may reduce costs and help to meet the Paris Agreement goals early. The expansion would require governments to set up policies and incentives that encouraged research and development into geothermal technologies and sub-surface exploration to encourage the development and expansion of geothermal technologies.

Conclusions

Geothermal is a baseload technology that increases grid stability and meets significant energy resilience needs, without intermittency, additional costs for storage, which wind and solar cannot offer. This leads us to argue that in the future, geothermal energy may provide flexibility with dispatchable power to

megacities as geothermal power plants are developed. Geothermal power plants are also much less space-consuming and have lesser impact on landscape compared to wind and solar.

Analysis of the geothermal potential for the megacities: Bogotá, Los Angeles, and Jakarta, reveals that the estimated RGB can meet present day residential energy consumption. Calculated RGB/Consumption ratios reveal geothermal can respectively provide 1.14, 4.25, and 1.84 times the energy demand for these megacities.

In scenarios where geothermal replaces the present-day energy produced by fossil fuels it is estimated that the decarbonizing potential of geothermal in Bogotá, Los Angeles, and Jakarta, could be 15.4–17.0, 20.9–25.1, and 6.9–7.9 MtCO₂e. In modest scenarios where geothermal is introduced and offsets 20% of the current fossil fuel use, thus developing only the most cost-effective resources, it is estimated that geothermal can contribute to 3.1–3.4, 4.2–5.0, and 1.4–1.6 MtCO₂e decarbonization based on present day energy use assumptions.

We argue therefore that Megacities would benefit from the sustainable and resilient form of energy to supply decarbonizing not only residential but also industry, transportation, and other needs. Critical to the uptake of geothermal energy, however, is a positive government action that may include a carbon tax, investment into research and development of geothermal resources, and the establishment of policies or tax breaks that encourage the exploration and development of geothermal resources. The execution of long-term investment policies into the research and development of geothermal energy is critical not only for improving the chances of economic exploration, but also in speeding up the rate of innovation and the safe and sustainable use of geothermal resources. Finally, if geothermal solutions are investigated, and proper promotion is presented to communities, then additional benefits of a low-carbon energy system may be found, allowing to reach near-zero emissions globally in 2050, raising the quality of life for many people and helping to reduce energy poverty.

Methodology

The concept of GRB refers to the thermal energy Q stored in volume V of rock in the subsurface. It is usually estimated using the volumetric heat in place (VHIP) approach²⁶. It depends on both thermal rock properties and the distribution of the geothermal gradient. Although this approach provides a general idea of the thermal energy on large scales, significant uncertainties remain due to the variability of the medium of variables such as density ρ , porosity Φ , heat capacity C , and temperature contrast (ΔT) in the region of interest. This method is based on Eq. 1, where the subscript r refers to rock and w to water. In this work, we assumed typical values of ρ , Φ , and C reported in literature^{46–52}.

$$Q = [(1 - \Phi) * \rho_r * C_r + \Phi * C_w * \rho_w] V * \Delta T \quad (1)$$

However, determining the potential geothermal power is difficult due to the scarcity of available information. Furthermore, uncertainties relating to newer AGS techniques and their efficiency at mining heat vs. utilizing hydrothermal waters to extract heat are still open for debate, since commercial developments are still not commonplace. Therefore, assessing a pure-play thermal resource is not included in this analysis.

In the three areas of interest, the GRB assessment is based on estimates from O&G wells and associated spring-waters. Using the EMAG2 database⁵³, there are estimations of the Curie Point depths (CPDs) for these areas ranging between 15 and 30 km⁵⁴. Hence, we calculated geothermal gradients. Generally, the most surficial CPDs match with areas of the largest density of spring waters (LDSW). In those areas, we defined regional plays with

geothermal gradients higher than 30 °C/km. In cases such as the northern Bogotá, where there are limitations in resolution of the EMAG2, we integrate it with the local magnetic databases⁵⁵ to improve the resolution and geometry of estimations of the CPDs by using the code Pycurious^{56,57}. Details of the method and parameters used are provided in the online data repository. We assumed that geothermal gradient anomalies may be responsible for the heating of the water springs dislocated along the fault systems and their complex intersections. We simplify the model and hypothesize, firstly, that the tectonic features control the location of hot spring-waters and secondly, that the area encompassing the springs can be used to define the area and volume of potential reservoir that is storing the thermal energy. Therefore, we assume the elliptical envelope that encompasses the LDSW as the best alternative for a better constraining of the area. While the areas, depths, and thicknesses of recoverable resources have been assumed according to the regional geology of the three areas, average porosity of 5%, fluid heat capacity of 4000 J/kg °C, rock heat capacity of 850 J/kg °C, specific heat capacity of 920 J/kg °K, and efficiency as low as 0.1% have been set as general values for the three areas. Table 3 summarizes the main volumetric parameters used for estimating the potential geothermal energy^{26,27}.

The Curie depth point, or that depth at which rocks lose their permanent magnetic properties due to temperatures near or higher than the isotherm 580 °C, is typically estimated using the radial power spectra of magnetic anomalies within overlapping rectangular windows regularly spaced in a region of interest. In this work we have used the approach proposed by Bouligand⁵⁶ to estimate the thickness of a buried magnetic source by fits an analytical solution to the entire power spectrum.

The method used and implemented in the code Pycurious⁵⁷, fits an analytical function that depends on three terms: the depth to the top of magnetic sources z_b , the thickness of magnetic sources Δz , and a fractal parameter β . The theoretical function that represents the radial average of the logarithm of the power spectrum of magnetic anomalies randomly distributed in the subsurface is defined by the next two equations⁵⁸:

$$\Phi_{B1D}(k_H) = C - 2k_H z_t - k_H \Delta z - \beta \ln(k_H) + \ln \left[\int_0^\infty (\cos(k_H \Delta z) - \cos(k_z \Delta z)) \left(1 + \left(\frac{k_z}{k_H} \right)^2 \right)^{-1-\frac{\beta}{2}} dk_z \right] \quad (2)$$

$$\Phi_{B1D}(k_H) = \int_0^{2\pi} \ln[\Phi_{B2D}(k_x, k_y)] d\theta \quad (3)$$

where $\Phi_{B1D}(k_H)$ and $\Phi_{B2D}(k_x, k_y)$ are the radial power spectrum and the 2D power spectrum of magnetic anomalies, respectively, $\vec{k}_H = (k_x, k_y)$ is the wave number in the horizontal plane, $k_H = |\vec{k}_H|$ is its norm, and θ is its angle with respect to k_x . The orientation of the geomagnetic field appears only in the constant C , and the shape of the radial power spectrum is independent of the direction of the geomagnetic field⁵⁸. In this work, we evaluated diverse size of windows and after an optimization process, the Pycurious code found the best parameters z_b , Δz , β , and C . Overlapping of windows was of 10 km, covering all area bounded between 1.5–8.5 N and 70–77 W, and presenting results for the window 3.5–6.5 N and 72–75 W.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Received: 31 December 2020; Accepted: 12 January 2022;

Published online: 18 March 2022

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Acknowledgements

The authors are grateful to the DAAD (Project 57448047: Geothermal Energy for Megacities: Phase 1, Bogotá - Colombia) and MINCIENCIAS (Projects 80740-053-2019, 110185271555-852-2019, 80740-909-2020, and 80740-157-2018) for funding the projects and allowing the academic exchange between the Friedrich-Alexander University (Erlangen-Nürnberg) and the Universidad Nacional de Colombia—UNAL (Bogotá). Geophysical monitoring infrastructure, including GHG stations in the campus of the UNAL, is being supported by TIGO—Colombia. Harald Stollhofen and two anonymous reviewers are greatly acknowledged for the constructive criticism and guidance that helped shape the final version of this paper.

Author contributions

L.C. and C.A.V. initiated the study in 2019 based on an idea to study the challenges of energy within megacities. C.A.V., L.C., and P.J.B. wrote the manuscript. C.V. developed the statistical model for geothermal resources, P.J.B. computed the forecast of heating and cooling needs for global warming scenarios and the emissions reduction scenarios.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43247-022-00386-w>.

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Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Alessandro Rubino, Joe Aslin, Heike Langenberg.

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