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Potential Geothermal Energy Resources of India: A Review

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Abstract India has planned to satiate the country's growing energy demand by the year 2040. For sustainable growth, the country must optimize the use of available energy sources (conventional and renewable) in an environment-friendly manner. Since India is the third largest country in the world emitting greenhouse gases, it is very important to increase the share of renewable and green energy sources like geothermal energy, solar power, wind energy, etc. in the energy portfolio. While there has been a significant increase in solar and wind energy production, geothermal energy is yet to be exploited. India has several potential geothermal fields predominantly controlled by the high heat-producing granites are located in different parts of the country. Planned production of electricity from these fields is 850 GWh/year by the year 2020. A wet geothermal system, as well as enhanced geothermal system, can be utilized to generate electricity at low production cost. Moreover, some of these fields are also rich in helium content which can be extracted to be utilized for domestic purposes.

Keywords Geothermal energy · Provinces · India · Heat flow · Thermal springs · Enhanced geothermal system

Introduction

Energy-intensive industrial production is growing rapidly in developing countries such as China and India. Currently, coal fills much of the growing energy demand as large coal reserves exist with limited reserves of other energy sources. Hydrocarbon-based energy sources that include coal, oil, natural gas, biofuels, woods, and other derivatives pose a great threat to the environment as they emit carbon-dioxide, one of the greenhouse gases, during extraction of power from them. As shown in Fig. 1, a major portion of anthropogenic CO_2 emission in the environment is related to the energy production and only a minor portion of CO_2 is emitted from the waste, agriculture, and other processes [1•]. According to the reports of the World Meteorological Organization (WMO), the CO_2 concentration in the atmosphere has increased significantly over the past century from about 280 ppm to around 400 ppm which is 142 % higher than the pre-industrial time [2, 3] with an average growth of approximately 2 ppm/year in the last 10 years. Global CO_2 emissions increased by 56 % between 1990 and 2013, and the IEA [4] projects that CO_2 emissions would increase to 36.7 Gt in 2040, 16 % higher than in 2013. Nearly two thirds of global emissions of 32.2 Gt CO_2 for 2013 originated from just ten countries, with the share of China (28 %), the USA (16 %), and India (5.8 %). Combined, these three countries alone produced ~16 Gt CO_2 [4].

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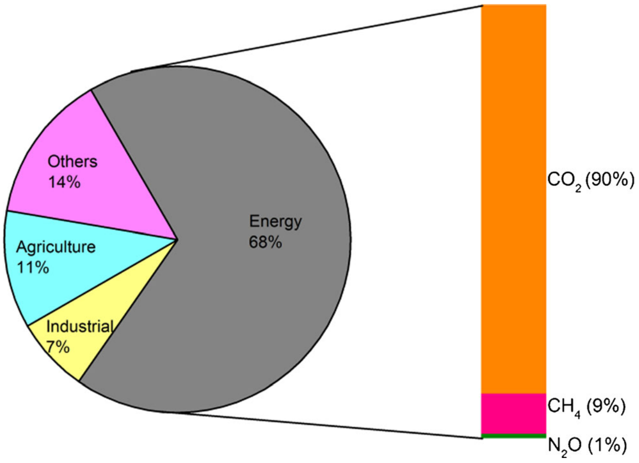

Fig. 1 Share of anthropogenic greenhouse gases emissions (modified after IEA [1•])

A significant amount of CO_2 emissions comes from burning coal which is extensively used for electricity and heat generation in countries such as Australia, China, India, Poland, and South Africa that produce over two thirds of their electricity and heat through the combustion of coal. About 42 % of global CO_2 emissions in 2013 came from electricity and heat generation only [4] out of which 73 % came from the consumption of coal. While the use of oil in electricity and heat generation has declined steadily since 1990, the use of natural gas increased slightly. However, the share of coal increased significantly, from 66 % in 1990 to 73 % in 2013 [4].

The growth in energy demand mostly comes from non-OECD (Organization for Economic Co-operation and Development) countries. China became the world's largest energy consumer in 2009 and it makes up 23 % of global energy demand [5•, 6]. India is the world's third largest consumer of energy after China and the USA. However, as the Indian population exceeds that of China in the late 2020s, the demand growth in India takes over from China and by 2040, India's energy demand approaches that of the USA [5•, 6]. Consequently, India's share of greenhouse gases in the environment from the consumption of fossil fuel-based energy sources is set to increase.

For sustainable development, therefore, it is imperative that alternative sources of energy be brought to the mainstream which could reduce CO_2 significantly and also save other resources like water, land, etc. In recent times, there have been tremendous developments in solar technologies worldwide for the conversion of sunlight into usable energy forms. Efficient wind turbines have been developed to generate electricity from wind energy. However, 1 MW electrical power generation from solar energy or wind energy requires 5–7 acres of land for installation of photovoltaic cells or windmills, whereas a geothermal power plant requires only 1–2 acres of land [7•]. The efficiency of a geothermal power plant is much higher than that of the solar or wind power plants, and it will work 24/7 and can take the base load power. Therefore, geothermal energy could be considered as the alternative source of energy and assessment of the potential fields may be required. It is essentially about harnessing the vast reserve of heat in the shallow subsurface efficiently. This paper gives the detail idea about the geothermal resources of India.

Earth's Heat

Sources of the Earth's internal heat are mainly: (a) radiogenic heat produced by the decay of naturally occurring radioactive isotopes such as potassium, thorium, and uranium; (b) primordial heat—the release of heat due to the formation of the Earth; and (c) heat generated from the release of gravitational potential energy by the transfer of material from shallower to deeper depths [8]. The temperature inside the Earth increases from the surface towards the center and consequently, the heat flows constantly from the Earth's interior to the surface. The heat outflow varies with location on the surface of the Earth depending upon the tectonic settings and geographical locations [9]. A measure is known as *Geothermal gradient*, i.e. the rate of increasing temperature with depth is commonly used to locate anomalous geothermal areas. Temperature gradients can be measured in boreholes and deep mines. The temperature gradient between 10 and 25 °C per kilometer of depth is considered as normal geothermal gradient, commonly observed on a stable plate away from tectonic plate boundaries. Dickson, Fanelli [10] observed large differences in the temperature gradients in various tectonic units of the earth's crust. Most of the geothermal systems are associated with the subduction zone and/or volcanic areas where the rocks are highly fractured or faulted due to the tectonic activity [11]. Sometimes, these faults traverse down very deep forming a thermal anomalous zone, helping the circulation of the meteoric water, and bringing the earth's heat to the surface in the form of thermal springs [11]. These thermal spring sites are a good indication for the potential geothermal sites and could be used for power generation and other purposes like space heating, fish farming, etc. In some areas, geothermal gradients are found to be five to ten times more than the normal values [10]. Heat energy of such geothermal anomalous areas can be tapped by drilling suitable wells. Natural steam and hot waters thus obtained from geothermal wells are being exploited in many parts of the world for various purposes, including power generation [12].

Geothermal Power Generation World Overview

Italy pioneered the use of the geothermal system for power generation by establishing the "first" geothermal power plant of 20 kW capacity at Larderello in 1905. This power plant was expanded to 40 kW in 1908 which enabled the electrification of most of the city of Larderello [13]. The first commercial geothermal power plant was developed in 1913 as *Larderello-1*, with installed capacity of 250 kW. At the end of 1943, the total installed capacity was 132 MWe in the region [13]. Geothermal power generation in Italy is only in Tuscany where the total installed capacity reached 915 MWe with 37 units and a production of 5916 GWhe by the end of 2014 [14]. A large number of geothermal fields have been explored and exploited in a different part of the world. Power generations by the countries from 1990 to 2015 are listed in Table 1 with a total capacity of about 12,633.1 MWe.

Indian Geothermal Provinces

Nearly 400 thermal springs have been reported from India till date [15]. Early investigations of thermal springs in Maharashtra, Madhya Pradesh, Uttar Pradesh, and Bihar with the general description, chemical characteristics of the springs from various records are reported by Chatterjee [16]. Gupta, Rao [17] constructed a general geothermal picture of the terrestrial heat flow from widely distributed locations in India. After the 1970s energy crisis, the Geological Survey of India (GSI) conducted reconnaissance surveys on the viable geothermal sites. The studies were funded under the United Nations Development Programme (UNDP), and the results were published in several of the GSI records and special publications [18, 19]. Subsequently, under a joint collaborative research between India and CNR-Italy (Consiglio Nazionale delle Ricerche), fluids from many of the thermal springs were analyzed between 1996 and 2000 and the results were published in several international journals [20–32].

Detailed geological and geophysical studies of several geothermal provinces [33–35], as well as geochemical characteristics of the thermal fluids and estimation of reservoir temperature, have been carried out by several workers [22, 23, 36–50•]. The need of an in-depth exploration program on the thermal springs has also been emphasized during several national and international conferences [7•, 26, 51]. This paper

Table 1 World total installed capacity of geothermal power plant (in MWe) from 1990 to 2015 (modified after Bertani [90])

Country	1990	1995	2000	2005	2010	2013	2015
Argentina	0.7	0.6	0	0	0	0	0
Australia	0	0.2	0.2	0.2	1.1	1	1.1
Austria	0	0	0	1	1.4	1.4	1.2
China	19.2	28.8	29.2	28	24	27	27
Costa Rica	0	55	142.5	163	166	207.1	207
El Salvador	95	105	161	151	204	204.4	204
Ethiopia	0	0	8.5	7	7.3	8	7.3
France	4.2	4.2	4.2	15	16	17	16
Germany	0	0	0	0.2	6.6	11.9	27
Guatemala	0	33.4	33.4	33	52	48	52
Iceland	44.6	50	170	322	575	664.4	665
Indonesia	144.8	309.8	589.5	797	1197	1341	1340
Italy	545	631.7	785	790	843	875.5	916
Japan	214.6	413.7	546.9	535	536	537	519
Kenya	45	45	45	127	167	248.5	594
Mexico	700	753	755	953	958	1017.4	1017
New Zealand	283.2	286	437	435	628	842.6	1005
Nicaragua	35	70	70	77	88	149.5	159
Papua New Guinea	0	0	0	39	56	56	50
Philippines	891	1227	1909	1931	1904	1848	1870
Portugal (Azores)	3	5	16	16	29	28.5	29
Romania	0	0	0	0	0	0	0.1
Russia	11	11	23	79	82	81.9	82
Taiwan	0	0	0	0	0	0	0.1
Thailand	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Turkey	20.6	20.4	20.4	20.4	82	405	394
USA	2774.6	2816.7	2228	2544	3093	3389	3450
Total	5831.8	6866.8	7974.1	9064.1	10716.7	12010.4	12633.1

identifies suitable geothermal sites for both power generation and direct use.

Seven geothermal provinces have been identified based on the tectonic elements of India and heat flows/geothermal gradients estimated from the thermal springs in those provinces as shown in Fig. 2 [51]:

i. Himalaya geothermal province
ii. Sohana geothermal province
iii. West coast geothermal province
iv. Gujarat-Rajasthan geothermal province
v. Godavari geothermal province
vi. Mahanadi geothermal province
vii. SONATA geothermal province

Himalaya Geothermal Province

Three important tectonic elements developed due to the continental collision between the Indian plate and Eurasian plate:

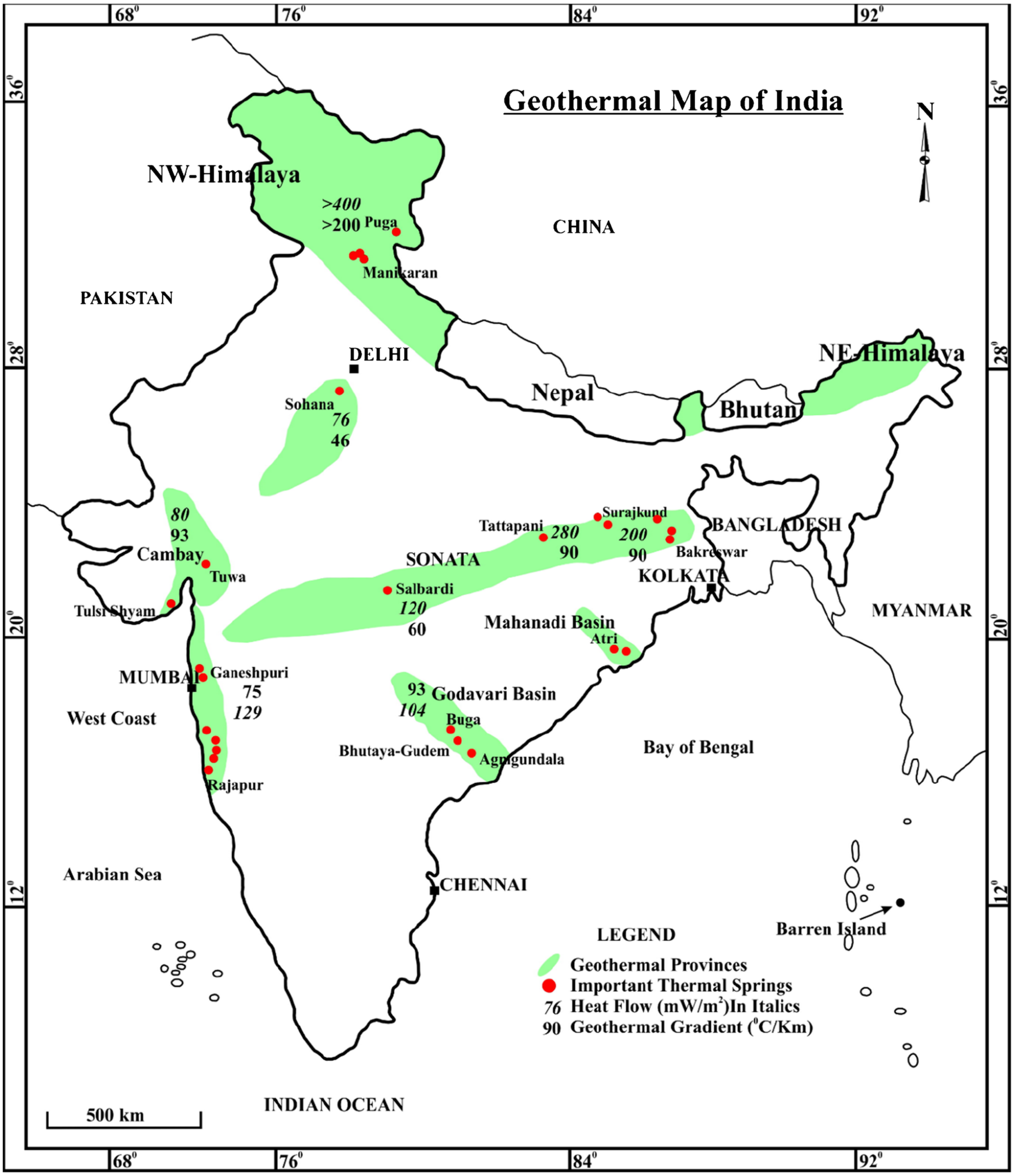

Fig. 2 Geothermal provinces of India (modified after Chandrasekharam, Chandrasekhar [51])

(1) main boundary thrust (MBT), (2) main central thrust (MCT), and (3) the Indus suture zone (Figs. 1, 2, and 3).

Metamorphic and granites (8–10 km thick) from the deeper level of the crust are exposed to its present position in the Higher Himalayas [52]. These young granites (3.5 to 60 Ma of age), also known as leucogranites, are exposed and spread all along the Indus suture zone (Fig. 3) [11, 53–60].

The present day observed heat flow (>100 mW/m^2, Fig. 4) all along the geothermal belt is caused by both tectonic subduction and shallow crustal melting [11, 61]. Using Na-K-Ca contents in the thermal waters, the reservoir temperature of the deep thermal water is estimated to be around 200 °C [62]. Based on the mixing models, the deep equilibration temperature obtained for the Manikaran geothermal field ranges between 120 and 140 °C [36]. However, cations and silica geothermometers give reservoir temperatures between 150 and 250 °C [20]. Manikaran thermal water is considered to be immature, and the low temperature of the reservoir is because of the fact that dissolved silica gets precipitated with falling temperature [32].

Sohana Geothermal Province

This geothermal province is located about 24 km south of the city of Gurgaon in Haryana (Fig. 2). The emerging temperatures of the thermal waters in the area range from 28 to 47 °C. Thermal activity is localized by deep circulation of the ground water in a tectonic depression developed by down-faulting of a central block lying between two anticlinal ridges belonging to the Delhi mobile belt [63]. Furthermore, Deb, Ray [63] suggested that the area has higher than the average geothermal gradient for a Precambrian area and estimated it to be in the order of 22 °C/km. GSI [18] estimated the geothermal gradient of 41 ± 10 °C/km and heat flow of 100 ± 25 mW/m^2. From several boreholes drilled in this area, the maximum temperature recorded is 55 °C from a depth of 547 m [64].

West Coast Geothermal Province

Eighteen thermal springs have been located along the west coast with surface temperatures varying from 47 to 72 °C (Fig. 2) [25••, 45, 49]. These thermal springs emanate through 65-Ma-old Deccan Flood Basalts (DFB). Chandrasekharam [65] and Minissale et al. [25••] suggest that the *west coast fault*, a major tectonic feature, along the west coast of India controls all the geothermal springs in this geothermal province. Based on gravity inversion, Negi et al. [66] suggest that the thinning of the lithosphere (~18 km thick) along this province caused shallowing of 1250 °C isotherm (at ~20 km depth). Thus, the high thermal regime at shallow depth results in high heat flow (75–129 mW/m^2) [11]. The geothermal gradient calculated from the borehole surveys is about 57 °C/km [31]. The temperature of the thermal waters of the west coast sub-provinces were estimated using gas and cation geothermometry, and it ranges from 120 to 150 °C [25••, 49].

The schematic as shown in Fig. 4 suggests the mechanism of the geothermal manifestations along the west coast. Many thermal springs along the west coast are believed to be issuing through the Deccan Basalt. However, Rajapur thermal springs located along the west coast shows different characteristic

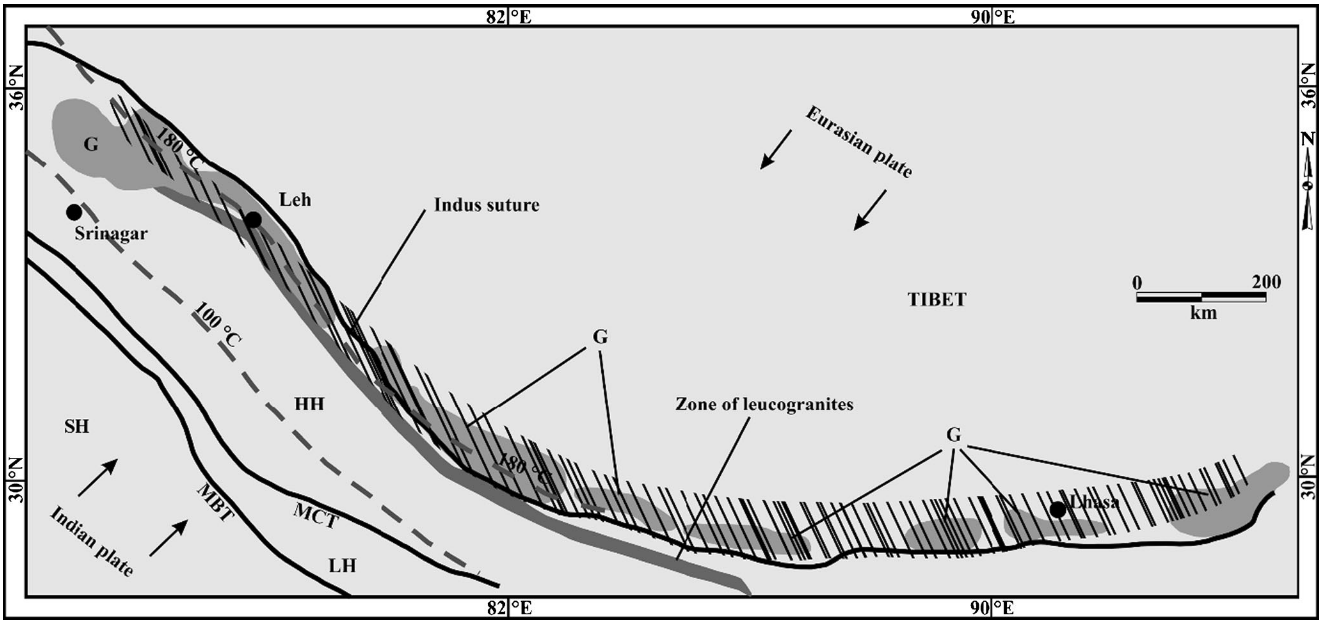

Fig. 3 General geology and tectonic feature of Himalaya (modified after Chandrasekharam, Bundschuh [11])

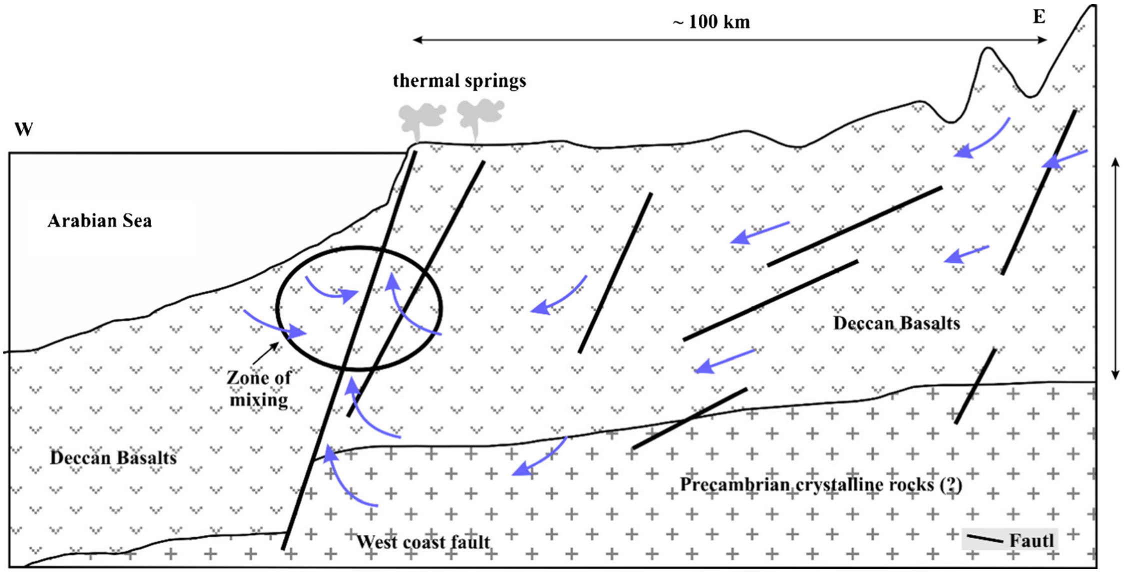

Fig. 4 Geothermal fluid circulation along the west coast of India (modified after Chandrasekharam, Bundschuh [11]). *Blue arrow* shows the circulation of water

from other west coast thermal springs. Reinvestigation of the Rajapur thermal springs shows that the thermal waters may be circulating within the granitic rock below the Deccan as well [49, 67].

Gujarat-Rajasthan Geothermal Province

Gujarat

Several thermal springs (about 22 of them) have been reported from the Gujarat geothermal province, with surface temperature varying from 35 to 93 °C [24••]. These are essentially located in the Cambay basin, a rift basin that is elongated in a north-south direction. The basin is bound by two deep-seated north-south oriented faults on the east and the west. This fault system extends down to mantle depth [68]. The basin was formed during the Late Cretaceous and has rotated anticlockwise during the post-northward drift of the Indian plate [69]. The high surface temperature of the thermal waters (93 °C) is observed near granite intrusives such as the Godhra granite (955 Ma of age, Gopalan et al. [70]) outcrop on the basinal margin near Tuwa [43]. Besides the two major faults bordering the basin, several ENE-WSW trending fault systems are present in this basin. A NE-SW geological section of the basin is shown in Fig. 5.

The SONATA rift axis cuts the Cambay fault system towards the SE part of the rift basin [24••]. The depth to Moho varies from 32 to 36 km in the Cambay basin, giving rise to a positive gravity anomaly of +35 mGals, high geothermal gradient (70 °C/km), and high heat flow values (67–93 mW/m^2) [11, 24••].

Rajasthan

This part of the geothermal province lies towards the eastern part of Rajasthan (North of Cambay and Sohana) and consists of Archean to recent lithological units. The NE-SW-oriented graben structure in the southern part of Rajasthan developed during the Precambrian and is filled with fluvial and lacustrine deposits [71]. There are several NE-SW trending faults developed due to cyclic and dynamic movement of the blocks. These fault systems provide conduits for deep circulating geothermal waters [24••, 43]. The surface temperature of the geothermal waters ranges from 31 to 50 °C, and the estimated reservoir temperatures vary from 120 to 150 °C [24••, 50•]. The maximum recorded heat flow value in the area is 205 mW/m^2 [50•].

Godavari Geothermal Province

The Godavari geothermal province is a tectonically active zone with a NW-SE-oriented graben structure. The basin is filled with post-Gondwana sediments with hydrocarbon generation potential. Several thermal springs have been reported from this geothermal province with surface temperature ranging from 30 to 62 °C, and the estimated temperature gradient is about 45 °C/km [64]. The maximum recorded heat flow in the area is 104 mW/m^2 [51].

Mahanadi Geothermal Province

Thermal springs in the Mahanadi province are reported along rifted granites and granite gneisses. These granites have a higher concentration of U, Th, and K as compared to the granites of Central India and the Himalayas and therefore,

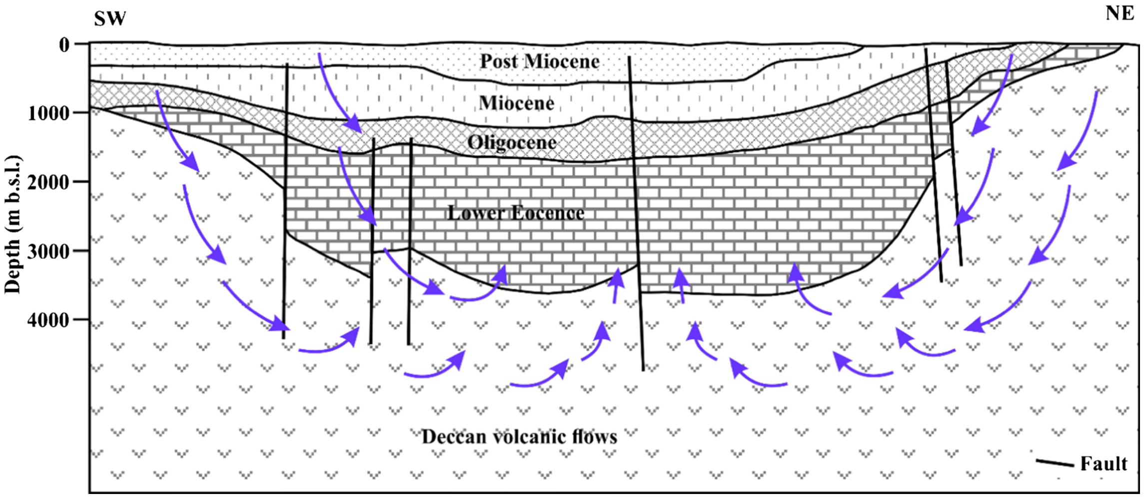

Fig. 5 Structure and lithology of Cambay geothermal field (modified after Chandrasekharam, Bundschuh [11]). *Blue arrow* shows circulation of ground water

they have high heat-generating potential [51]. From the reported 8 geothermal springs, the reservoir temperature estimated using Na-K and K-Mg geothermometers is about 180 °C [51].

SONATA Geothermal Province

The SONATA rift system was formed due to the interaction between the two protocontinents during the early stages of development of the Indian plate [72] and was reactivated after the collision of the Indian plate with the Eurasian plate [34, 73]. Deep reflection seismic profiles across the SONATA, south of Tattapani, suggest that the fault system reaches the mantle [68]. The Tattapani springs are located at the eastern edge of the SONATA geothermal province and are related to the Balarampur fault system [40••]. A schematic cross-section showing the geology and structure of the Tattapani geothermal system is shown in Fig. 6.

The entire SONATA province has a sedimentary insulation over granitic intrusive at about 2 km depth [74] producing a geothermal gradient of 60 °C/km. The surface temperatures of the geothermal waters at Tattapani vary from 30 to 93 °C. From detailed geochemical studies, Chandrasekharam, Antu [40••] estimated the reservoir temperature of the Tattapani geothermal field in the range of 205 to 217 °C. They also suggest the minimum depth of the reservoir be around 3 km assuming an average geothermal gradient of 80 °C/km. The presence of high helium content in the thermal waters is indicative of the presence of a high amount of radioactive minerals in the Precambrian rocks responsible for high geothermal gradient at Tattapani. Furthermore, the shallow occurrence of granitic intrusives below Gondwana sedimentary rocks makes SONATA one of the best enhanced geothermal systems in the country.

Another group of thermal springs in this geothermal province is observed at Bakreswar and Tantloi (Fig. 2).

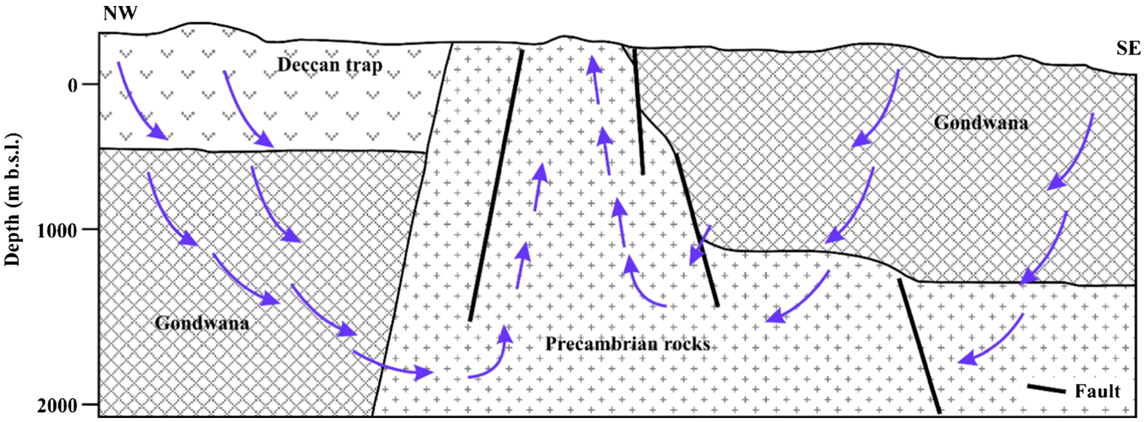

Fig. 6 Geology and structure of Tattapani geothermal field located parallel to the SONATA rift (modified after Chandrasekharam, Bundschuh [11]). *Blue arrow* shows water circulation in the subsurface

These thermal waters have a surface temperature in the range of 42 to 72 °C [47, 75]. Majumdar et al. [76] suggest that these thermal springs are getting recharged somewhere in the vicinity of the Gondwana basin along the central part of the Chotanagpur plateau. From audiomagnetotellurics (AMT) studies around the Bakreswar geothermal field, Sinharay et al. [77] suggested that the location of geothermal reservoir is deep and lies on the northwestern side of the Bakreswar thermal springs and the N-S fault close to the Bakreswar field is a shallow feature, not deeper than 300 m, that cannot act as a heat source. The recent geochemical investigations of Bakreswar and Tantloi thermal waters show the reservoir temperature between 130 and 140 °C; however, a shift in the oxygen isotope suggests that the reservoir temperature could be even higher than the estimated one [75, 78••]. Thermal gases from Bakreswar and Tantloi have high He content (1.5 %) and low Kr/Xe ratio (0.262), suggesting radiogenic heating of the thermal waters circulating through granites [79–81]. This is further supported by high heat flow values of 69 mW/m2 in this area [31, 82]. The environment for circulating water appears to be similar to Tattapani thermal springs in Chhattisgarh. The thermal gases in Tattapani springs also has high He content (1.54 %) [25••] with high heat flow (107 mW/m2) [51, 82].

The Surajkund geothermal area in the Sonata geothermal province (Fig. 2) has a geological setting similar to that of Bakreswar and Tantloi. The emerging surface temperature of the Surajkund thermal water is 89 °C and the estimated reservoir temperature is 190 °C [78••]. Thus, both the deep-seated fault system of SONATA and radiogenic heating from granites appear to be the main heat source for circulating thermal springs in this geothermal province [79].

Thermal waters in the Rajgir-Munger hot springs have extremely low chemical content dissolved in the waters (~40 mg/l), and surface temperature ranges from 35 to 50 °C. These hot springs emerge from the fracture and joint planes of Precambrian quartzites and phyllites [47]. Based on chemical geothermometers, the reservoir temperature is estimated to be in the range of 60 to 95 °C [47, 83].

Enhanced Geothermal System of India

The geothermal systems discussed above are the wet geothermal systems where the heat sources are faulted and fractured and have a active water circulation system. However, there are heat sources which can be utilized by fracturing and transferring heat by circulating fluid through them. These are called enhanced geothermal systems. Granites with high heat-generating capacity, in the range of 1.5 to 16.5 $\mu W/m^3$, are found throughout the Indian continent. The geothermal provinces identified above have high heat flow values ranging from 75 to an excess of 200 mW/m^2. The estimated temperature at a depth of about 1.5 km is in the range of 150 to 180 °C and increases to more than 220 °C at a depth of 4 km [84]. Some of the younger granites such as the leucogranites along the middle of Himalayas are located at shallow depths (~5–7 km) due to the anatectic melting above to the subducting continental slab [84–86]. These leucogranites have an enhanced geothermal system (EGS) reserve of about 61160×10^{12} kWh. The high heat-generating granites in Madhya Pradesh (area 1000 km^2) have a reserve of about 24464×10^{12} kWh and in Andhra Pradesh (now is Telangana) have a reserve of 111200×10^{12} kWh [61].

Jhunjhunu and Siwana granites of Rajasthan have high heat production of 16.48 and 16.47 $\mu W/m^3$, respectively, which are the highest in the Indian shield [50•]. These are radiogenic heat produced due to the abundance of U, Th, and K isotopes. Furthermore, the highest heat flow is obtained from the Tosham granite area of Malani Igneous Suite which is on an average 96 mW/m^2. The concentration of U, Th, and K isotopes in Siwana granites is up to 37.03 ppm, 165 ppm, and 5.32 wt%, respectively [50•].

The Bundelkhand granite and gneissic complex is the host of the geothermal system at the Tattapani area. These granites have high U (3–8.8 ppm), Th (6.9–42.5 ppm), and K (1.4–4.6 wt%) contents and the heat generation capacity varies from 1.4 to 5.4 $\mu W/m^3$ [87].

The above areas are best suited to initiate EGS projects. However, they require high startup capital as the development of these projects requires extensive drilling and fracturing of granites. However, with the advancement in technology, heat extraction becomes economic for power generation to meet the growing demand of electricity in India.

Power Generation Cost

A geothermal power plant is essentially a hydrothermal convection system which captures earth's heat energy in the form of steams coming out of the drilled wells and converts it into electricity through different motors. Wells are drilled at geothermal hotspots to circulate water through reservoirs of high heat capacity. A geothermal plant can generate electricity for 25–30 years or longer depending on how the field is developed and maintained. Geothermal power is one of the most affordable renewable energy resources. As such, there is no fuel cost involved and maintenance or ancillary costs are minimal. Considering the entire life cycle of a geothermal power plant, the overall capital cost and operational cost is significantly lower than many other technologies for electricity generation.

Estimating the total cost of a geothermal power project towards computing its unit cost to the end user and comparing it with different energy options is a very complex task. The upfront capital required for a geothermal power project varies

Table 2 US average levelized costs (at 2013 USD) for plant entering production in 2020

	A	*B*	*C*	*D*	*E*	*F*
Conventional coal	85	60.4	4.2	29.4	1.2	9.51
Advanced coal	85	76.9	6.9	30.7	1.2	11.57
Advanced coal with CCS	85	97.3	9.8	36.1	1.2	14.44
Conventional combined cycle	87	14.4	1.7	57.8	1.2	7.52
Advanced combined cycle	87	15.9	2	53.6	1.2	7.26
Advanced CC with CCS	87	30.1	4.2	64.7	1.2	10.02
Conventional combustion turbine	30	40.7	2.8	94.6	3.5	14.15
Advanced combustion turbine	30	27.8	2.7	79.6	3.5	11.35
Advanced nuclear	90	70.1	11.8	12.2	1.1	9.52
Geothermal	92	34.1	12.3	0	1.4	4.78
Biomass	83	47.1	14.5	37.6	1.2	10.05
Wind	36	57.1	12.8	0	3.1	7.36
Wind-offshore	38	168.6	22.5	0	5.8	19.69
Solar PV	25	109.8	11.4	0	4.1	12.53
Solar thermal	20	191.6	42.1	0	6	23.97
Hydroelectric	54	70.7	3.9	7	2	8.35

Costs in columns B, C, D & E are in US$/MWh, whereas costs in column F are in US¢/kWh. Costs are expressed in terms of net AC power available to the grid for the installed capacity. As modeled, hydroelectric is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season (source: EIA [88])

A capacity factor, *B* levelized capital cost, *C* fixed O&M, *D* variable O&M, *E* transmission investment, *F* levelized cost

across the countries. The viability of the renewable energy option is mostly based on the tax structure in the country [46, 88]. The cost of power generation depends on the subsidies provided by the respective government. A study [89] that modeled diverse scenarios of power generation in California concluded that as most geothermal projects had the lowest overall cost, consumers would benefit from higher geothermal power production.

For comparative costs analysis of different technologies, the US Energy Information Administration [88] published *levelized costs* for a unit of electric power generated from different sources. Table 2 gives the levelized cost (at 2013 USD value) for the power generating sources of energy that will be entering production in the year 2020. Such data gives a summary measure of the broad competitiveness of different energy sources involved in generating electric power in the USA. These values act as guidelines to project costs for renewable and evaluate them against the savings through reduced CO_2 emissions. In all respect, the geothermal source for electricity is very competitive (Table 2) and with maturing technologies (design of highly efficient heat exchangers and drilling rigs) the cost of unit power will further decline. Perhaps the levelized unit cost of power from EGS source will also further decline.

Power Generation Using Geothermal Energy

As described above, India has two types of geothermal fields, the wet geothermal system and enhanced geothermal system, which can be used for power generation to meet the electricity demand. Currently, in India, there is no power generation from the geothermal energy source. However, planned construction of 35 MWe geothermal power plant is going on. Projected use of geothermal energy by 2020 is 850 GWh/year with installed capacity of 100 MWe [7•]. Most of the geothermal systems in India are in the low-enthalpy geothermal system category. Therefore, it is suggested that these areas can be effectively used for power generation using binary cycle technique known as Organic Rankine Cycle (ORC). Essentially, in this technique, heat is extracted from the geothermal fluid through a heat exchanger and is transferred to a low boiling point (BP) organic liquid which in turn evaporates and develops sufficient pressure to drive the turbine. Selection of working fluid is the most important part in ORC. The working fluid should have a low BP and it should evaporate at atmospheric pressure. It should be non-corrosive, non-flammable, and non-reactive at the working temperature and pressure. However, in practice, all the requirements may not be met as many organic fluids are inflammable and not environmentally friendly. The main advantage of organic working fluid is that the turbine chamber need not be under the vacuum condition.

Table 3 Thermodynamic properties of some working fluids for binary power plants (modified after DiPippo [91•])

Fluid	Formula	Tc (°C)	Pc (MPa)	Ps @ 300 K MPa	Ps @ 400 K MPa
Propane	C3H8	96.95	4.236	0.9935	n.a.
i-Butane	i-C4H10	135.92	3.685	0.3727	3.204
n-Butane	C4H10	150.8	3.718	0.2559	2.488
i-Pentane	i-C5H12	187.8	3.409	0.09759	1.238
n-Pentane	C5H12	193.9	3.240	0.07376	1.036
Ammonia	NH3	133.65	11.627	1.061	10.3
Water	H2O	374.14	22.089	0.003536	0.24559

Tc critical temperature, *Pc* critical pressure, *Ps* steam pressure

Table 3 shows thermodynamic properties of some working fluids in comparison with pure water. All the working fluids have lower values of critical temperature (Tc) and pressure (Pc) as compared to that of water. Since the hydrocarbons have low values of critical pressures, they could be considered for the supercritical cycles. In the binary cycle n-butane (BP −0.5 °C) and isobutane (BP −11 °C) are the most suitable for a low-enthalpy geothermal system [11].

The organic fluids used in ORC are also considered as greenhouse gases (GHGs); therefore, they can potentially attract environmental concerns. To overcome this problem, in 1983, Dr. Alexander Kalina used a simple mixture of ammonia and water to run the engines that is now known as the Kalina cycle. Since both liquids have different boiling points (BP of ammonia −33 °C; BP of water 100 °C), different ratios of the liquids in the mixtures give a wide range of boiling temperatures for the low-enthalpy geothermal systems. Furthermore, turbines in the Kalina cycle are smaller in size and less expensive as compared to the ORC turbines [11].

Conclusions

Energy demand in India is continuously growing because of a rising population and industrial development. Sustainable development requires concerted effort to exploit various forms of renewable energy while reducing GHGs in the environment. While the share of solar and wind energy in India's energy portfolio is increasing, unfortunately, there has been no geothermal power production till date. However, projected energy use from geothermal power is 850 GWh/year with installed capacity of 100 MWe by the year 2020. This would come from exploitation of both the wet geothermal system and enhanced geothermal system. Granites with high heat capacity can be exploited by inducing fractures and developing an artificial geothermal reservoir. Heat from the source is transferred to the circulating fluid which could then be used for power generation. Various estimates suggest that economics of geothermal power is favorable when compared with other forms of renewable energy. India has the potential to produce geothermal energy at a cost of US¢ 4.75/kWh. Additionally, in those areas where thermal gases are enriched in helium (He), commercial production of He can be planned. In Bakereswar and Tantloi geothermal areas, a pilot plant to extract and purify He from thermal gases is already in operation.

Compliance with Ethical Standards

Conflict of Interest Hemant K. Singh, D. Chandrasekharam, Trupti G., P. Mohite, B. Singh, Varun C., and S.K. Sinha declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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