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GENERATION OF ELECTRICITY USING CARBON DIOXIDE FROM WASTE EMISSIONS AS A WORKING FLUID IN GEOLOGICAL SUBSURFACE

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ABSTRACT

Geothermal energy is described as the process of extracting the heat generated by the earth and harnessing it to produce electricity. Geothermal energy is capable of providing clean, consistent, reliable electricity production even without the need for grid scale energy storage unlike the renewable energy alternatives such as solar energy, wind energy, etc..In present scenario, 22 billion tonnes of CO_2 *are emitted into the atmosphere from human sources which are considered as waste and also the biggest reasons for the promotion of Global warming through GHGs.* CO_2 *Plume geothermal technology (CPG) involves capturing the* CO_2 *from waste emissions such as coal fired power plant using CCUS technology and injecting it into natural, highly permeable geologic formations to extract energy. The* CO_2 *in the subsurface absorbs heat from the reservoir, buoyantly rises to the surface and drives power generation system. In this paper, we have analysed the thermodynamic and fluid mechanical properties of* CO_2 *suggesting that the* CO_2 *from emissions can be used as best working fluid in subsurface to harness significant amount of energy from geologic heat. Production of electric energy along with its supply in conjunction with CCUS can improve economic viability of* CO_2 *Sequestration which is the major hurdle for its large scale implementation in India and all around the world. Further we present the simulation results demonstrating the potential of geothermal energy capture of CPG compared to other geothermal systems and its implications on geologic* CO_2 *sequestration in terms of economic viability in the Indian context.*

Keywords: Carbon Dioxide Plume Geothermal energy (CPG), Engineered Geothermal Systems (EGS), Carbon Capture Utilization and Sequestration (CCUS), Indian Geothermal resources.

I. INTRODUCTION

Due to rapid economic development there has been significant increase in energy demands. Consequence of increasing energy demands has resulted into heavy use of fossil fuels (i.e. coal, oil and natural gas) that have become key energy resources since the industrial revolution. Impact of abundant use of fossil fuel is the major concern because of its adverse effects on environment specially due to the emission of CO_2, a major anthropogenic greenhouse gas (GHG). As per the Emission Database for Global Atmospheric Research, global

CO_2 emission was 33.4 billion tonne in 2011 which is 48% more than two decades ego. Over the past century, atmospheric CO_2 level has been increased by more than 39%, from 280 ppm during pre-industrial time to the high level of 400 ppm in May,2013 with increase off 0.8°C in the surface temperature. Without appropriate climate change mechanism it's possible that greenhouse gas emission would increase to 25-90% by 2030, over the level of 2000, with concentration of 600-1550 ppm in environment. By contrast, it is estimated that the CO_2 emission should be controlled by 50% for limiting the rise of global temperature by 2°C by 2050.

Efforts for controlling anthropogenic CO_2 emissions in environment requires that existing and emerging technologies should move away from using fossil fuels and move towards renewable resources. Carbon dioxide sequestration in deep saline aquifers, exhausted oil bed and natural gas fields has potential for mitigating CO_2 in atmosphere as a counter measure to global warming. Rather than treating CO_2 from emissions as waste, it can be utilised as best working fluid in geologic formations to capture energy due to its excellent thermodynamic and fluid mechanical properties. Advances in CCS technology will improve the feasibility of CCUStechnology, however upcoming advances may not be sufficient to encourage large scale CCS implementation. Combining CCS technology with renewable energy capture, electricity production and also improve the economic viability of CCS thereby leading towards CCUS.

Indian geothermal provinces have enough potential to meet the scarcity of electricity of entire nation but it's often underrepresented in renewable energy discussions [8]. New technologies and methods such as CPG will prove critical for future investments and rapid implementation of geothermal technology so that it could play a vital role in Indian energy landscape.

1.1 CO_2 from Emissions – Excellent working Fluid

Carbon dioxide as working fluid for heat extraction has been discussed earlier in terms of EGS [6]. The favourable properties of CO_2 as per Brown can be listed as follows:

- CO_2 possesses low kinematic viscosity that allows effective heat advection
- The density of CO_2 varies much more with temperatures than that of water which generates strong thermosyphon through the injection and production wells thereby reducing the pumping needs for circulation of subsurface fluids as that of traditional geothermal systems.
- Diminishing fluid mineral reactions upto a small region which will migrate as the CO_2 plume grows.

Considering the above points we further evaluated thermophysical and fluid mechanical properties of CO_2 comparing with water so as to define its functionality in CPG system and also for predicting that its better than water as working fluid.

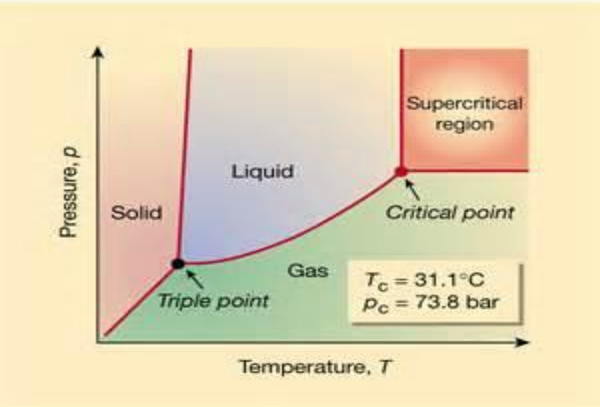


Fig.1. Phase States of CO_2(Source: www.nature.com)

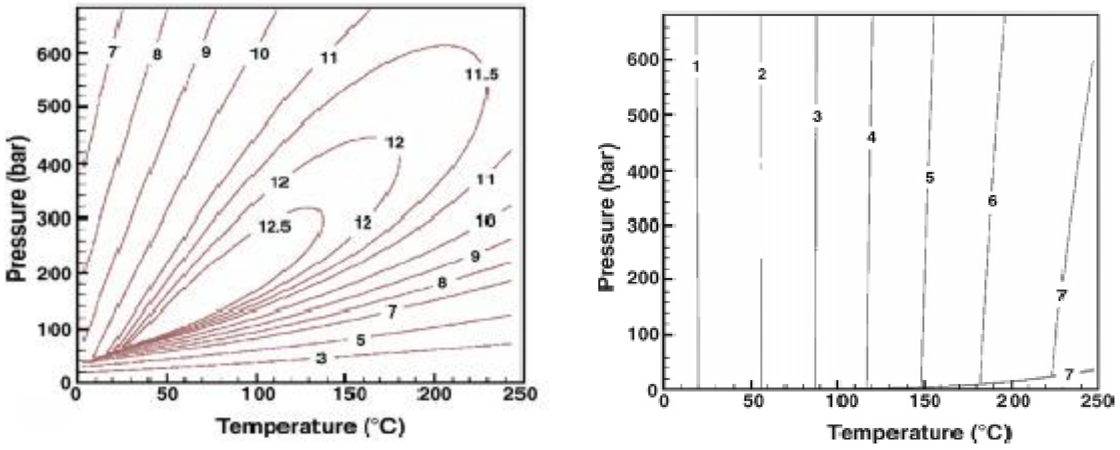
At critical point CO_2exhibits T_{crit}=31.04°C and P_{crit}=73.82bar (Figure 1), which are of great interest from injection and production point of view. CO_2 can exist in two different phases, liquid and gaseous state, as well as two-phase mixtures of these states. Supercritical CO_2 forms a phase distinct from aqueous phase and can change simultaneously into either gaseous or liquid CO_2 with no phase boundaries. Supercritical carbon dioxide can also be used in colder conditions as compared with water based geothermal systems, since it has low freezing point of about -55°C. Fluid's mass flow rates for any given driving force is proportional to the ratio of density to viscosity,

$$m = \rho/\mu \quad (1)$$

The sensible heat carried by mass flow rates is proportional to fluid's specific enthalpy. Parameters essential important for mass flow and heat transfer behaviour includes,

$$Compressibility\,(c) = (1\,/\,(\rho))(\delta\rho\,/\,\delta P) \quad (2)$$

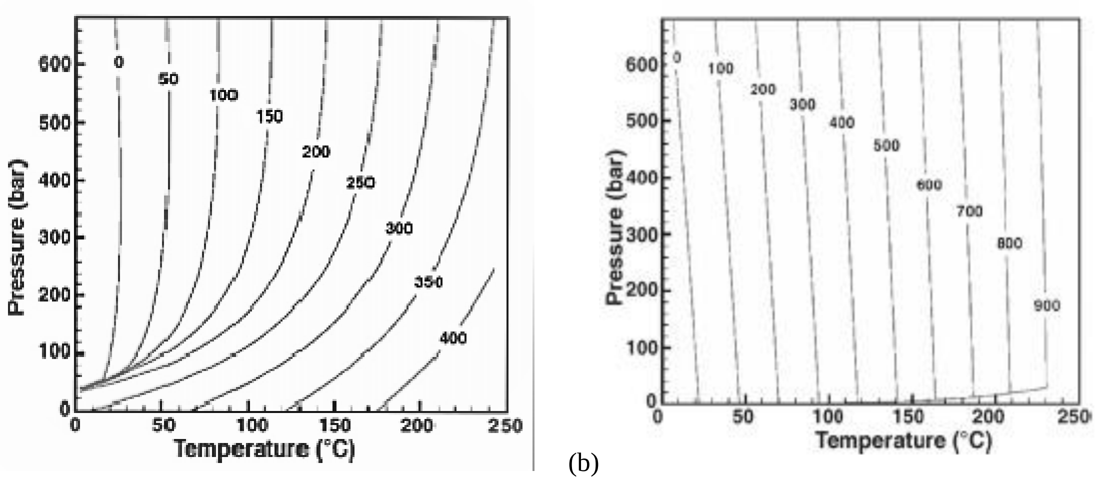
$$Thermal\ expansivity\,(\varepsilon) = -(1/\rho)(\delta\rho/\delta T) \quad (3)$$



(a) (b)

Fig.2. (a) Fluid density to viscosity ration in 10^6 s m^{-2} for CO_2; (b) Fluid density to viscosity ratio in 10^6 s m^{-2} for water

Fig.2 and Fig. 3 shows the thermophysical properties of CO_2 and water. Properties of CO_2 were calculated from the correlations of Altunin (Altunin, 1975). Water properties were obtained from the steam table equations given by the International Formulation Committee (IFC, 1967). The ratio of density to viscosity is comparatively larger than for water and dependence on temperature and pressure was found to be much different for the two fluids. In case of water ratio is mostly a function of temperature and only least of pressure that reflects the primary dependence of both water's density and viscosity on temperature. In case of CO_2, density and viscosity have significant dependence on both Temperature and pressure. The variations observed are in such a way that (ρ/μ) attains maximum value in a region of intermediate temperature and pressures that extends beyond the CO_2 saturation line, becoming smaller for liquid-like CO_2 (low T, high P) and for gas like CO_2 (high T, low P). For (T, P)-conditions relevant for fluid injection, $T \leq 50$°C, (ρ/μ) for CO_2 is larger than for water by factors ranging from 4 to 10. For temperatures near 200°C,(ρ/μ) for CO_2 is larger by a factor of approximately 2 than that of water.



(a) (b)

Fig.3. (a) Specific enthalpy of CO_2; (b) Specific enthalpy of water, in units of kJ/kg, as function of temperature and pressue

A comparison of the specific enthalpies for CO_2 and water is as shown in Fig.Considering both cases the reference state (zero enthalpy) was chosen as (T, P) = (20°C, 100 bar). At high pressure of about 500 bar, the increase in specific enthalpy with temperature for CO_2 is less than half of the increase of water, indicating that more than twice the CO_2 mass flow rate would be needed to achieve the same rate of sensible heat transport. Specific enthalpy of liquid water depends mostly on temperature and least on pressure. For CO_2 the pressure dependence was found to be weak for its liquid like conditions, but becomes increasingly strong at lower pressures and high temperatures. For adiabatic (thermally insulated) decompression, thermodynamic condition will act along isenthalps. Accordingly, decompression of hot, high pressure CO_2 will be accomplished by substantial temperature decline, while for liquid water there will be a small temperature increase. Table 1 shows that CO_2 is more compressible than water, and has larger expansivity as well, especially at lower temperatures. Fluid densities will therefore vary much more than for water with pressure and temperature changes. Because of these reasons the geothermal systems can also be deployed successfully in the regions of lower subsurface temperature and lower permeability than those currently deemed economically favourable for geothermal development.

Table 1. Density, Compressibility and expansivity of CO_2 and water measured at selected temperature and pressure conditions

T (°C)	P (bar)	CO_2			Water		
		ρ (kg m^{-3})	Compressibility(Pa^{-1})	Expansivity (°C^{-1})	ρ (kg m^{-3})	Compressibility (Pa^{-1})	Expansivity (°C^{-1})
20°C	100	856.251	1.490×10^{-8}	8.607×10^{-3}	1001.76	3.489×10^{-10}	1.944×10^{-4}
	500	1048.77	2.484×10^{-9}	2.696×10^{-3}	1015.94	3.538×10^{-10}	1.448×10^{-4}
200°C	100	122.184	1.076×10^{-7}	3.036×10^{-3}	870.798	8.377×10^{-10}	1.321×10^{-3}
	500	581.322	1.274×10^{-8}	3.172×10^{-3}	900.990	8.668×10^{-10}	1.077×10^{-3}

1.2. Carbon Dioxide Plume Geothermal (CPG) System

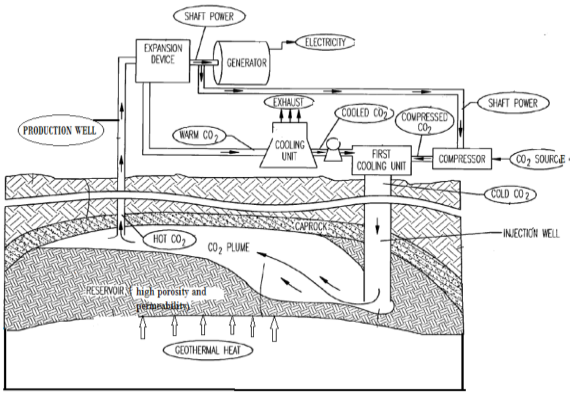


Fig.4. Simplified and Schematic one possible implementation of CO_2 Plume Geothermal (CPG) system

CPG technique generates energy from waste CO_2 which is emitted by sources. The sources can be waste stream from power plants such as fossil fuel power plant, ethanol plant, cement manufacturing industries, steel manufacturing industries, etc. which are considered as major CO_2 emitting sources having concentration of 15-30% by weight in flue stream. The CO_2 is captured using CCS technologies after which it can be transported through pipelines direct to geothermal plant for direct use in target formations. The target formations comprising caperock and reservoirs can be made up of variety of rock types such as igneous rocks, metamorphic rocks, limestone, sedimentary rock, etc. CPG involves injecting supercritical CO^2 into deep, naturally porous and permeable geologic formations prevalent worldwide (e.g. Cambay province in India), where the CO_2 displaces native formation fluids that might be brine or hydrocarbons as present in standard sequestration or enhanced oil recovery, and then it is heated by the in-situ heat and background geothermal heat flux. A portion of the heated CO_2 is then piped back to the surface and sent through an expansion device, powering a generator and producing electricity or is sent through heat exchanger to heat a secondary working fluid in a binary power system or to provide energy for district heating. The CO_2 is then re-injected into the reservoir and stored through geologic formations.

Engineered geothermal systems are typically generated by hydro-fracturing or stimulating hot dry rocks of low natural permeability, but this process may induce seismicity because the critical fractures stresses in geologic formation are intentionally exceeded. Enhanced geothermal system (EGS) can be deployed in the region having high temperature or low permeability geologic formations to increase the power production but EGS is found to be controversial (e.g. Basel in Switzerland, 2009). In contrast to water based EGS and CO_2-EGS, CPG systems will produce electricity by CO_2 that has been heated by geological heat due to sequestration in a sedimentary basin utilizing its high permeability and high porosity geologic reservoirs overlain by a low permeability trap such formations are found worldwide. In India, sedimentary basins suitable for sequestration are available offshore and onshore such as Gondwana sedimentary formations in Godavari geothermal province [8]. CPG doesn’t rely on any kind of hydro-fracturing or similar permeability enhancing technologies thereby avoiding drawbacks in implementation in EGS Systems. Consequently the CO_2 sequestration potential of the CPG system is larger than that of EGS as the target formations are sedimentary basins having low permeability have large quantity of CO_2 storage options. Hence, this approach can be distinguished from EGS.

II. NUMERICAL SIMULATION METHODOLOGY

In this section, various CO_2 based geothermal systems in a naturally porous, permeable aquifer, i.e. the CPG system is compared with CO_2-EGS and Conventional water based geothermal system. The also develop the numerical simulations to estimate the geothermal heat energy extraction rate in the CPG approach for the purpose of calculating the electricityprovided per ton of sequestrated CO_2 in Indian geological scenario. The most critical geothermal reservoir and fluid injection/production parameters in an early stage analysis are reservoir permeability, temperature, pressure, dimensions, and fluid injection/production rate. In a numerical exercise, there is comfort for adjusting the parameters as desired within the limits as per the assumed natural systems.

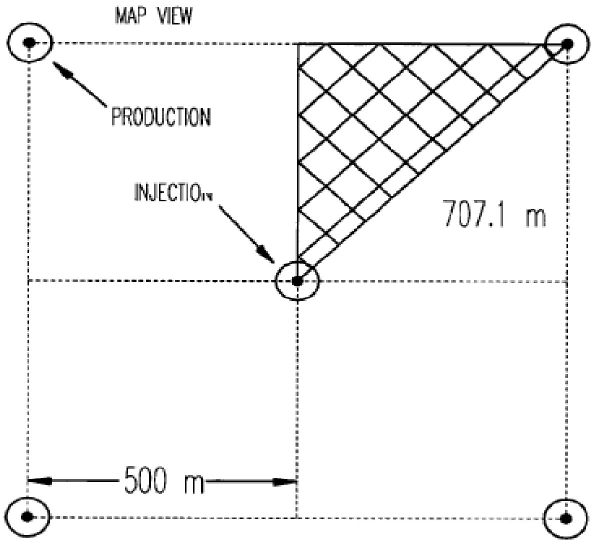


Fig.5. Five spot well configurations considered for simulations. As per symmetry, gridded section of the given view is to be simulated

For simulation purpose we are considering a base case model, a geologic reservoir with moderate thermal characteristics which may be encountered in moderate to low geothermal heat flow regions across India. Initial temperature of subsurface formations is kept as 100°C, often considered as the lower limit for geothermal electricity production [e.g. Hulen and Wright, 2001]. In a region with low to moderate geothermal gradients (30-35°C/km), T = 100°C corresponds to a reservoir depth of around 2.5km (250 bar) mainly depends on local mean annual surface temperature and fluid/rock thermal conductivity. For such low reservoir temperatures and heat flow rates, it’s reasonable to assume hydrostatic pressure [Sanyalet. Al., 2007].Such temperature and pressure values are feasible in almost all the favourable geothermal provinces in India.

A five-spot well configuration (Figure 5) was utilized for simulation purpose, as this geometry is typical of early stage geothermal system models and also approximates real-worlds, water based geothermal installations. The model thus provides

$$H = Q(h - h_0) \tag{4}$$

Where, h is the enthalpy of produced fluid and h_0 is the enthalpy of injected fluid.

In this simulation, the system is assumed to contain only CO_2 as well as all water. Displacement of formation's native fluids by CO_2 is important but it's not the part of our present study. All the parameters are enlisted below. All the simulations are performed using TOUGH 2 reservoir simulator using ECO2N module.

Table 2. Complete list of parameters and conditions considered for simulations, all parameters for the additional caes are not specifically defined are to be taken as base case

Parameters for Base Case			
Geological formation		**Injection/Production conditions**	
Thickness	305m	Temperature of fluid injected	20^{o} C
Separation of injection & production well	707.1m	Rate of Injection/production	280 kg/sec to max. 300 kg/sec (variable)
Permeability	5 x $10^{-14}m^{2}$	Bottom hole injection pressure	260 bar
Porosity	0.2	Bottom hole production pressure	240 bar
Rock grain density	2650 kg/m^{3}	Duration of Injection/production	25 years
Rock specific heat	1000J/kg/^{o} C	Map area of formation	1 km^{2}
Thermal Conductivity	2.1 W/m/^{o} C		
Initial Conditions		**Boundary conditions**	
Fluid injected	Pure CO_2 as well as Pure water	Top & sides	No fluid /heat flow
Temperature	100^{o} C	Bottom	Heat conduction, no other fluid flows
Pressure	250 bar		
Parameters defined for additional cases			
Case	Temperature	Depth	
1	150^{o} C	4 km (400 bar)	
2	100^{0} C	1 km (100 bar)	

III. SIMULATION RESULTS AND DISCUSSIONS

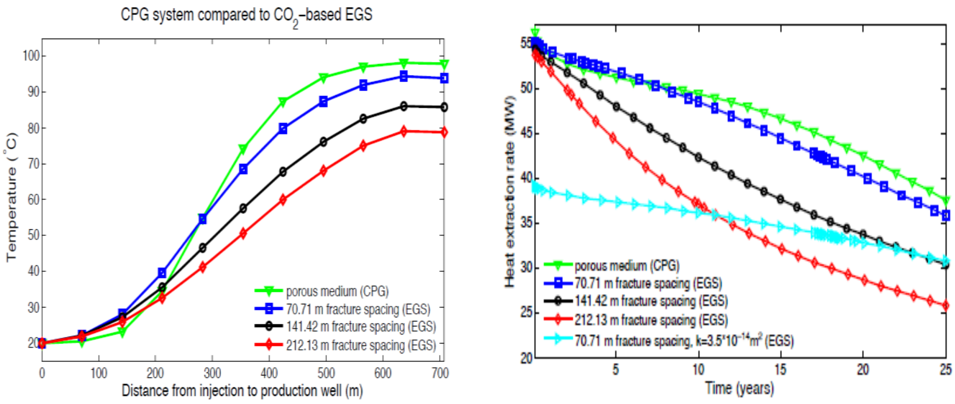


Fig.6. (a) Temperature versus Distance from injection well to Production well for a porous medium in CPG System and for various fracture spacing in EGS System; (b) Heat extraction rate versus time for a porous medium in CPG system and for various facture spacings in EGS system

3.1. Comparison of CPG System with CO_2-EGS Systemand Water based geothermal system

Specifically, Fig. 6(a) compares CPG System with conventional CO_2-EGS system using various average facture spacing (200m, 100m, 50m, from bottom to second from the top), thus providing the cross section through the model geometry from injection to production well. Surprisingly, there are substantial differences between CPG and EGS models. In CPG system, near pre-production temperatures were maintained at the production well for much longer time than in EGS models. Results show that there was more through thermal energy recovery in CPG systems as compared to EGS system. So it's expected that CPG system will achieve higher efficiency and maintain economic viability longer than conventional EGS. Simulation suggests that after 10 years of injection, CPG system exhibit maximum reservoir temperature than EGS System. Since electricity production in geothermal energy is direct proportional to fluid temperature, CPG system provides higher temperature than EGS system. Finally, as the study reveals, in EGS system the wider the fracture spacing, the lower will be the temperature of produced fluid. Thus, all being equal, CPG systems can be implemented in low temperature geologic formations as the case in India.

Fig. 6(b) compares heat energy production rates as a function of time for CPG and CO_2-EGS systems. For given pressure difference, CPG system produces 1.75 times more heat energy than CO_2-EGS system. For producing the same amount of heat energy, CO_2-EGS requires much higher pressure difference almost by the factor of two between injection and production well. Thus the EGS has greater pumping energy requirement and lower power production efficiency than the CPG systems.

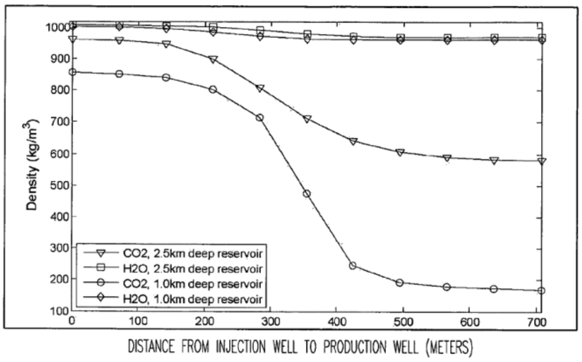


Fig.7. Density versus Distance from injection well to production well for a CPG system as compared to a water system

Fig.7. provides the density profiles of injection to production wells, comparing the CO_2 and H_2O based geothermal system for two variant depths. These results are applicable for both CPG and EGS system. CO_2 systems allows for large density changes in CO_2 between wells as compared to water based system. Such change in density from production to injection wells is named as thermo-siphon effect due to which lower pumping requirements in CPG than water based system.

3.2. Energy recovery from CPG System

Results of simulations have been formulated in Table. Heat extraction rates are given on a full well basis and are averaged over the duration of fluid injection and production. Mass flow rates remains almost constant. Case 1 was considered for relatively deep reservoir in a moderate geothermal heat flow regions such kind formation may be encountered in Cambay geothermal provinces of India [8, 9]. Case 2 was considered for a shallow reservoir in a high heat flow regions which may be encountered in Himalayan geothermal provinces in India [7].

Table 3. Simulation results for one five spot well system stating heat extraction rates for CPG system

Simulation results	
Case	Heat extraction rate (average over 25 years)
Base Case	47.0 MW
1	62.6 MW
2	64.1 MW

IV. CONCLUSIONS

India has enormous potential of generating more than 10,600 MW of electricity through geothermal provinces but the development of this technology is still at nascent stage. India appears to be warehouse of high heat generating granites that indicates we have potential to generate electricity greater than projected requirements by the year 2030 and make our nation more energy independent. India had launched the most ambitious solar mission that was aimed to generate 20,000MW electricity by 2020, however, at present only 130 MW of electricity is in generation through this mission. Considering the cost of such renewables, water requirement, and land requirement, geothermal seems to be the most economical source that must be realized by our policy makers. Geothermal energy is blooming all over the world at unexceptional rate. India is still lagging in this area even though we have 400 thermal springs capable of generating 10600 MW of electricity.

The CPG system described in this paper is economically and practically simple in operation compared to other prevalent geothermal system that provides novel means for producing renewable energy in conjunction CCS technology, thereby providing process with negative carbon footprint. CPG system utilizes supercritical CO_2 having excellent thermodynamic, fluid dynamic and chemical properties as working fluid that provides us the new way for generating geothermal energy which was still not in limelight in Indian geothermal provinces. It also enhances the efficiency of geothermal plants in colder regions or during colder season as compared to traditional water based geothermal system. CPG systems are expected to be more compact than water based system thereby reducing plant's spatial and environmental footprint. In contrast to solar and wind power system, geothermal system are highly scalable, can provide electricity for base load and peak power requirements. Geothermal energy is renewable energy resource and once developed it will feed the nation with electricity at relatively cheaper rate than electricity generated coal, wind, nuclear, etc. CPG system also provides better heat energy extraction rate than EGS system as per the numerical modelling presented in this paper.

Numerical modelling also suggests that geologic reservoirs with CO_2 as working fluid could substantially offset the cost of CCS and most importantly the sequestration costs of CCS. Additional research is required, presently through all the simulation results and literature works we can conclude that CPS system are economically and technologically favourable for electricity production in the regions with relatively low - moderate subsurface temperatures and heat flow rates in Indian geothermal provinces. Since most of the geothermal provinces are in rural areas, development of geothermal projects can improve the rural electric supply for the growing markets and at the same time will also improve socio-economic status of our rural India by bringing thousands of villages under electricity grid.

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