



Utilization of carbon dioxide from coal-based power plants as a heat transfer fluid for electricity generation in enhanced geothermal systems (EGS)



Arun Ram Mohan^a, Uday Turaga^b, Vishakha Shembekar^c, Derek Elsworth^a,
Sarma V. Pisupati^{a,*}

^a John and Willie Leone Family Department of Energy and Mineral Engineering and EMS Energy Institute, The Pennsylvania State University, 110 Hosler Building, University Park, PA 16802, USA

^b ADI Analytics LLC, 14511 Old Katy Road, Suite 374, Houston, TX, USA

^c Omkar Scientific Solutions LLC, 3133 Buffalo Speedway Apt 1309, Houston, TX, USA

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ABSTRACT

The feasibility of using carbon dioxide (CO₂) as a heat transfer fluid by organic Rankine cycle (ORC) in enhanced geothermal systems (EGS) in arid regions is explored in this paper. As CO₂ is available for sequestration at high pressures from an Integrated Gasification Combined Cycle (IGCC) plant, this idea is examined by pairing an IGCC plant with an EGS plant to facilitate both the simultaneous extraction of geothermal heat and sequestration of CO₂ as well as power generation from EGS. The ORC portion of EGS was modeled by ASPEN Plus version 7.3. Four different working fluids were chosen for the ORC portion of the EGS to absorb the geothermal energy from the CO₂ in a binary heat exchanger. The power generated from the EGS and the lowest possible temperature at which CO₂ can be discharged from the binary heat exchanger was evaluated for each working fluid. The addition of a preheater provides an opportunity to add a second cycle so that both CO₂ and the working fluid can be discharged at the lowest possible temperature. In all cases, the thermal energy recovered from the EGS reservoir is substantially higher than that required to compress the CO₂ stream from the IGCC for sequestration.

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1. Introduction

Recoverable geothermal energy is available in low permeability sedimentary rocks and basement formations with low porosity. At a depth of 6.5 km from the surface, the thermal reserve is of the order of 1.1×10^6 EJ [1]. Assessment of enhanced geothermal systems (EGS) for commercial utilization of geothermal heat shows tremendous potential for electricity generation [2]. The conventional engineering and technology used to access oil and gas can be adapted for the extraction of geothermal energy provided it is capable of accommodating temperatures greater than 250 °C. Stimulation of the low permeability rocks comprising the geothermal reservoir is necessary as native permeabilities are typically in the micro-Darcy range. This is accomplished by hydraulic fracturing or hydraulic shearing to create and expand the reservoir, elevate fluid flow-through rates and increase the heat

transfer area of the reservoir. This facilitates the extraction of geothermal heat by creating a network of fractures that connects the injection wells with the production wells. In case of geothermal reservoirs with sufficient native permeability, techniques like water-flooding used for oil recovery are utilized for the extraction of geothermal heat [3]. Rock temperature in excess of 200 °C is preferable for the production of electricity from the resulting high enthalpy geothermal fluid [3]. The thermal energy is recovered from the reservoir by pumping the heat transfer fluid through the injection well deep into the subsurface and by recovering the hot fluid at the production well [4]. Modeling results show that approximately 40% of the thermal energy can be recovered from a stimulated reservoir of volume approximately 0.1 km³. The magnitude of the stimulated volume (0.1 km³) considered for these subsequent calculations, for a range of fracture spacing, permeability and well arrangements, is well below that achieved in the field. This improves the chances of recovering more thermal energy from the geothermal reservoirs [5].

The deepest geothermal well so far drilled in the United States is approximately 2.8 km and less than 100 geothermal wells are

* Corresponding author. Fax: +1 814 865 3248.

E-mail addresses: sxp17@psu.edu, spisupati@psu.edu (S.V. Pisupati).

drilled so far [3]. These wells are considered as shallow hydrothermal wells where the thermal gradient may be as high as 50 °C/km [3]. There are three advanced wellbore drilling technologies that will have potential applications in the construction and exploration of geothermal wells. Deep inside the wells, the pressure of the fluid (oil or gas) occupying the pores of the rock and the density of the rocks increase with depth. To avoid the blow out of these fluids from the well during the drilling process, the density of the drilling fluid has to be heavy enough to suppress the pressurized fluids within the pores of the rock and not light enough to fracture the rocks. In a certain range of depths, there is a narrow margin for the density of the drilling fluids within which the wells can be drilled safely. The drilling is done in stages where the diameter is largest at the top and smallest at the bottom of the well [6]. The reduction in diameter can be minimized by the expandable tubular casing process invented by Shell Oil, where an expandable device whose outer diameter is larger than the inner diameter of the casing is hydraulically pressurized to increase the outer diameter of the tube by 20% without compromising the strength of the tube [7–9]. The reliability of the process is yet to be proven in geothermal wells even though it has a potential to reduce the drilling cost of the wells. Another technique referred to as drilling with casing is also promising as it uses fewer and longer casings reducing the cost of well formation. These technologies have the potential to reduce the cost of the well formation by as high as \$ 3 million per well [3].

Around 11.2 GW_e of electricity is generated worldwide from geothermal energy [10]. As the temperature of the working fluid utilizing geothermal heat energy is much lower than that used in the combustion of fossil fuels, the Carnot efficiency of electricity generation from ORC is also lower. When water is used as a working fluid, the energy available for power generation from a supercritical fluid is significantly larger than in hydrothermal water at 200 °C. Utilization efficiency, defined as the ratio of actual power generated to the maximum possible power output, is between 25% and 50% for the current geothermal systems used in power generation [3]. When water is used as a geothermal fluid, the installed capital cost for power generation is approximately \$2.3/MW_e for the geothermal fluid temperature of 100 °C and \$1.5/MW_e when the geothermal fluid temperature is 200 °C [11]. The cycle thermal efficiency is estimated to be 22% at a resource temperature of 300 °C and 14% at a geothermal source temperature of 200 °C [12].

When water is used as a geothermal fluid for the extraction of geothermal heat energy, depending upon the available thermal energy in the geothermal fluid, there are four configurations possible for the conversion of geothermal energy into electricity. They are dry steam plants, single flash steam plants, double flash steam plants and binary steam plants. In dry steam plants, water injected into the geothermal well is recovered through the production well as dry steam. The production fluid will also contain non-condensable gases that typically account for 2% to 10% by wt of steam [13]. A cyclone separator removes all the rock debris and dust particles entrained in the steam. Expansion of the dry steam through an impulse/reaction type turbine produces power. As opposed to direct contact type condenser, a surface-type condenser is used for the condensation of steam so that the non-condensable gases can be treated for the removal of hydrogen sulfide [12]. As air-cooled condensers are uneconomical for small power plants, water-cooled condensers are used to condense the geothermal fluid. It is cooled in a cross-flow or counter-flow cooling tower and circulated back into the injection well to form a closed loop. The Geysers in northern California is an example where dry steam plant is used for the conversion of geothermal energy into electricity [12,13].

Predominantly, the geothermal fluid leaving the production well is a two phase mixture. The steam quality, indexed by the weight

percentage of the steam in the mixture, is determined by the reservoir fluid conditions, well dimensions and well head pressure. The well head pressure is typically 0.5–1.0 MPa. In a single flash steam plant, the two phase mixture is fed to the cylindrical pressure vessel cyclone separator to separate the primary high pressure steam from the water. The high pressure steam is fed to the turbine for power generation. The hot water is circulated through heat exchangers for direct heat applications. In a double flash steam plant, the high pressure hot water is flashed through a control valve for the generation of steam that is subsequently expanded in a low pressure steam turbine for the generation of additional power. The amount of liquid wasted without the utilization of geothermal heat is 30 times more in a single flash power plant compared to that in a dry steam power plant [13]. The amount of power generated by a double flash power plant is 20%–30% greater than that recovered from a single flash power plant [13].

Binary cycle plants use an organic Rankine cycle (ORC) where the geothermal heat is transferred from the geothermal fluid (water in most cases) to a working fluid. The direct contact between the geothermal fluid and the turbine, a feature typical in both single and double flash cycles, is avoided and prevent damage to the turbine vanes caused by small particles and non-condensable gases. Extensive studies have been conducted on the properties of working fluid that are suitable for the organic Rankine cycle [14–29]. The working fluids used in the ORC can typically be R134a for geothermal fluid temperatures as low as 100 °C [14,15]. For geothermal fluid temperatures greater than 200 °C, isobutane, isopentane, and a combination of mixture of fluids can be used [14,18].

2. Approach to the utilization of carbon dioxide for the extraction of geothermal heat

In arid regions, for example in the southwest part of the United States where subsurface temperatures are elevated, it is not feasible to use water as a geothermal heat transfer fluid due to its scarcity. An alternative geothermal heat transfer fluid that is cheap and abundant is necessary for the absorption of geothermal heat in these regions. In the year 2010, the total amount of CO₂ emitted from the energy and the industry sector in the United States is 5.6 gigatons [30]. Almost 34% of the total amount of CO₂ is emitted from coal combustion for electricity generation and coal utilization in the industrial sector [30]. Capture and sequestration of CO₂ emitted from power plants is necessary to mitigate climate change [31]. The objective of the paper is to explore the possibility of utilizing carbon dioxide as an alternative geothermal fluid for the extraction of geothermal heat in arid regions and to simultaneously sequester CO₂.

Air-blown combustion, oxycoal combustion and gasification are the three coal-based technologies that can be utilized for power generation [32–34]. The CO₂ stream produced from oxycoal combustion is concentrated compared to that obtained from air-blown combustion maximizing the storage space if CO₂ is sequestered. However, oxy-combustion requires that the supply air is pre-separated in the upstream portion of the boiler with attendant parasitic loads [33]. In both cases, compression of CO₂ to high pressures is necessary before sequestration. Post combustion carbon capture is suitable for air-blown and oxycoal combustion [32]. In Integrated gasification combined cycle (IGCC), the concentrated stream of carbon dioxide is separated from the synthesis gas by pre-combustion carbon capture methods at high pressures suitable for sequestration. Pre-combustion carbon capture is more cost effective compared to post combustion carbon capture [35]. The higher efficiency of power generation for IGCC (42% based on HHV) [32,35] combined with the economic method of separation of CO₂

makes this process an attractive option over the other two for pairing with the enhanced geothermal systems (EGS).

Fig. 1 shows the schematic representation of pairing an integrated gasification combined cycle (IGCC) plant with binary enhanced geothermal systems. CO₂ formed during the gasification and the subsequent water gas shift reaction process is separated at high pressures by pre-combustion carbon capture methods in an integrated gasification combined cycle (IGCC) plant so that it is ready for sequestration. The carbon dioxide ready to be sequestered is fed into the injection well for the absorption of geothermal heat energy. Short-circuiting flow of CO₂ from the injection well to the production well may result in rapid but incomplete thermal drawdown in the reservoir [36]. So the carbon dioxide is injected in a series of wells to attain a distributed sweep of fluid. The limited permeability of these reservoirs means that multiple injection wells and production wells are required to provide sufficient throughput in the reservoir. A portion of the injected CO₂ is lost in fractures in the rocks and this loss contributes to the sequestered inventory. The remainder of the CO₂ circulates through the reservoir and is the agent that removes the heat. The geothermal heat is transferred from the CO₂ to a working fluid in a heat exchanger and this working fluid passes through the organic Rankine cycle (ORC) for power generation. This power generated is in addition to that obtained from IGCC through the gas turbine and steam turbine. The IGCC plant is sized such that it produces sufficient CO₂ to compensate for the sequestration losses adjacent to the reservoir. This symbiotic pairing of CO₂-EGS with IGCC reduces both the usage of water in arid regions while simultaneously extracting heat from the reservoir and sequestering CO₂ in the subsurface.

3. Assumptions used in this study

The total amount of CO₂ injected into the geothermal well is 680 kg/s at a pressure of 15 MPa and at a temperature of 60 °C. In order to avoid premature depletion of the reservoir and limited by the anticipated low permeability of the stimulated reservoir [36], this flow is distributed equally among 10 injection wells so that 68 kg/s of CO₂ is injected into each well. 10% of the total CO₂ injected into the wells escapes through the fractures and contributes to the sequestered mass. The depth of the injection well and the production well are each assumed to be 6 km. The thermal

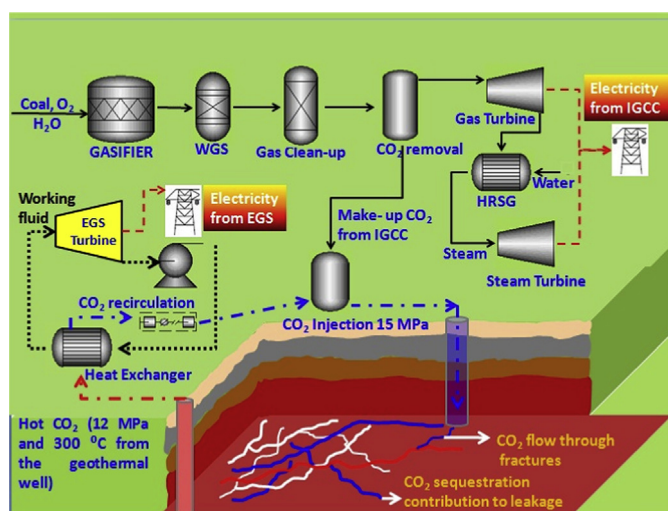


Fig. 1. Schematic representation of pairing an integrated gasification combined cycle plant (IGCC) with the Enhanced Geothermal Systems (EGS) using CO₂ as a geothermal fluid in arid regions.

Table 1

Ultimate Analysis of Pittsburgh no 8 coal on a dry basis [26].

| Elements | Composition wt% |
|----------|-----------------|
| Carbon | 75.65 |
| Hydrogen | 4.83 |
| Nitrogen | 1.49 |
| Sulfur | 2.19 |
| Oxygen | 6.63 |
| Chlorine | 0.11 |
| Ash | 9.10 |

gradient in the geothermal well is assumed to be 50 °C/km. The pressure drop of CO₂ from the injection well through the reservoir to the production well is assumed to be 3 MPa. The remaining CO₂ carries the geothermal heat and leaves the production well at a temperature of 300 °C and 12 MPa. It transfers the geothermal heat energy to the working fluid in the ORC through a binary shell and tube heat exchanger. The CO₂ lost to the geothermal reservoir during the sequestration process is compensated from a 315 MW_e IGCC plant using Pittsburgh no 8 coal. The ultimate analysis of Pittsburgh no 8 coal on a dry basis is given in Table 1 [37]. Assuming an efficiency of 42% HHV for the IGCC plant, based on the proximate analysis, ultimate analysis and the calorific value [37], the total amount of CO₂ produced from the 315 MW_e IGCC plant amounts to 68 kg/s. The summary of the calculations is shown in Table 2.

4. Modeling approach for the organic Rankine cycle in EGS

We modeled the binary organic Rankine cycle in ASPEN Plus V7.3 to determine the effectiveness of five different working fluids in the utilization of geothermal energy extracted when CO₂ is used as a geothermal heat transfer fluid. This fluid is then used to produce electricity from an enhanced geothermal system (EGS). Ammonia, neopentane, *n*-Butane and R134A are the four different working fluids chosen for the study. Peng–Robinson Equation of state was used to calculate the properties of all the fluids. Fig. 2 shows the process flow sheet created in ASPEN Plus for the geothermal heat extraction by CO₂ coupled with the organic Rankine cycle. 612 kg/s of CO₂ is recirculated back after transferring the geothermal heat energy to the working fluid in a shell and tube heat exchanger. 68 kg/s of CO₂ from a 315 MW_e IGCC plant is compressed to 15 MPa for sequestration. The total amount of CO₂ injected as geothermal fluid into the geothermal well is 680 kg/s at 15 MPa. A flow splitter is used to represent the mass rate sequestered in the geothermal reservoir where 10% of the total injected mass of CO₂ (68 kg/s) is assumed sequestered and is lost to the closed circuit. The remaining 90% of the CO₂ (612 kg/s at 15 MPa) is fed across the geothermal reservoir. The geothermal reservoir is modeled as a heater where the temperature of CO₂ is raised to 300 °C. The pressure drop from the injection well to the production well is assumed to be 3 MPa and represents the flow impedance of

Table 2

Calculation showing the amount of CO₂ emitted from an IGCC plant.

| | |
|---|----------------------|
| Electrical output of the IGCC power plant | 315 MW _e |
| Efficiency of an IGCC power plant | 42% |
| Thermal output of the IGCC power plant | 750 MW _{th} |
| Calorific value of Pittsburgh no 8 coal (HHV) | 31,000 kJ/kg |
| Amount of Pittsburgh no 8 coal consumed by the IGCC plant | 24.3 kg/s |
| Amount of CO ₂ emitted from a 315 MW _e IGCC plant | 68 kg/s |
| Leakage of CO ₂ through the geothermal well | 10% |
| Total amount of CO ₂ injected into the injection wells | 680 kg/s |
| Number of injection/production wells | 10 |
| Amount of CO ₂ injected through each well | 68 kg/s |

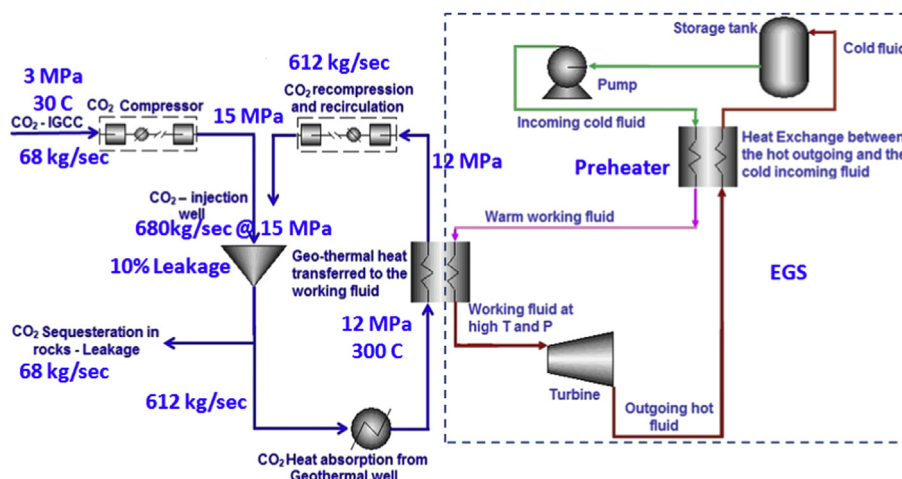


Fig. 2. Process modeling of organic Rankine cycle for producing electricity by EGS using CO₂ as a geothermal fluid.

the reservoir. The geothermal fluid (CO₂) is discharged from the heater (proxy geothermal reservoir) at 12 MPa and 300 °C. It enters the heat exchanger which is modeled by a MHEATX model in ASPEN PLUS. The geothermal heat is transferred from CO₂ to the working fluid. The CO₂ is recompressed to 15 MPa and circulated back to the flow splitter inlet. CO₂ lost in the sequestration process is compensated by the output from the IGCC plant (68 kg/s) so that a constant inlet flow rate of 680 kg/s can be maintained at the inlet of the flow splitter.

In the first part of the study, a preheater was not used in the ORC. The working fluid is chosen to be in liquid state. It is compressed to high pressure with a pump. In the absence of the preheater, it directly enters the binary heat exchanger to absorb the geothermal heat from the CO₂. The fluid passes completely to the vapor phase and the expansion of this fluid in the turbine to atmospheric pressure produces electricity. The vapor at atmospheric pressure is fed to the condenser to change phase from vapor to liquid. The cold liquid at atmospheric pressure is recirculated back into the pump. The power generated in this cycle was studied as a function of the five different working fluids when the temperature of the geothermal fluid at the heat exchanger inlet was 300 °C. The lowest possible temperature at which CO₂ can be discharged from the heat exchanger was also studied. In the second part of the study, a preheater was used. The hot working fluid in the vapor phase leaving the turbine outlet enters the preheater to heat the cold but high pressure liquid leaving the pump before it enters the binary heat exchanger to absorb the geothermal heat from the CO₂. The effect of the preheater in reducing the amount of energy wasted in condensation was studied for both neopentane and *n*-Butane. There are three constraints used in the modeling of the organic Rankine cycle. These are that: (i) there should not be any

temperature crossover either in the binary heat exchanger or the preheater between the hot and the cold fluid, in other words, the temperature of the hot fluid is always greater than the temperature of the cold fluid from one end to the other end of the heat exchanger (ii) that the working fluid should completely be in the vapor phase at the turbine inlet, and, (iii) that the working fluid should completely be in the vapor phase during expansion in the turbine or at the turbine outlet. The inlet conditions used for the working fluid are shown in Tables 3–6. These conditions are chosen to meet all the modeling constraints.

5. Error analysis

Based on the assumptions in Table 2, the ORC for the working fluids was modeled under specific conditions in ASPEN Plus. The results are reproducible under the same conditions. Therefore, error analysis is impertinent in this study.

6. Results and discussion

In the ORC, the pressure of the working fluid and its mass flow rate are the input conditions that determine the power output. The specific heat capacity and the thermodynamic properties of the working fluid determine the amount of power generated from the ORC for a certain amount of heat input. The amount of power generated, efficiency of power generation and the CO₂ exit temperature are shown in Tables 3–6 for ammonia *n*-Butane, neopentane and R134A respectively. The first law efficiency is defined as the ratio of net power output generated in the ORC to the geothermal heat energy absorbed by the working fluid from CO₂ in the binary heat exchanger.

Table 3
Power output from EGS and efficiency of power generation from EGS for ammonia.

| Mass flow rate of working fluid ammonia = 100 kg/s | | | | | |
|--|------------------------------------|---------------------------------------|---------------------------------------|-----------------------|------|
| Working fluid pressure (MPa) | Power generated (MW _e) | Exit CO ₂ temperature (°C) | Ammonia temperature in heat exchanger | | η % |
| | | | T _{in} , °C | T _{out} , °C | |
| 0.5 | 27.3 | 60 | -35 | 293 | 12.7 |
| 1.0 | 36.4 | 60 | -35 | 296 | 16.9 |
| 2.5 | 39.9 | 70 | -35 | 238 | 20.3 |
| 3.0 | 44.9 | 65 | -35 | 275 | 21.8 |
| 4.0 | 49 | 62 | -35 | 295 | 23.2 |

Table 4
Power output from EGS and efficiency of power generation from EGS for *n*-Butane.

| Mass flow rate of working fluid <i>n</i> -Butane = 300 kg/s | | | | | |
|---|------------------------------------|---------------------------------------|--|------------------------------|------|
| Working fluid pressure (MPa) | Power generated (MW _e) | Exit CO ₂ temperature (°C) | <i>n</i> -Butane temperature in heat exchanger | | η % |
| | | | <i>T</i> _{in} , °C | <i>T</i> _{out} , °C | |
| 5 | 42.9 | 20 | –1 | 225 | 18.7 |
| 10 | 45.7 | 20 | 2 | 253 | 19.8 |
| 15 | 46.4 | 20 | 4 | 266 | 20.1 |
| 20 | 46.5 | 20 | 6 | 274 | 20.2 |
| 30 | 45.9 | 20 | 10 | 285 | 20 |
| 40 | 45 | 20 | 14 | 292 | 19.5 |

Table 5
Power output from EGS and efficiency of power generation from EGS for neopentane.

| Mass flow rate of working fluid Neopentane = 100 kg/s | | | | | |
|---|------------------------------------|---------------------------------------|--|------------------------------|------|
| Working fluid pressure (MPa) | Power generated (MW _e) | Exit CO ₂ temperature (°C) | Neopentane temperature in heat exchanger | | η % |
| | | | <i>T</i> _{in} , °C | <i>T</i> _{out} , °C | |
| 5 | 39.8 | 50 | 12 | 268 | 16.4 |
| 10 | 42.5 | 50 | 14 | 289 | 17.5 |
| 15 | 40.6 | 55 | 17 | 286 | 17.7 |
| 20 | 40.6 | 55 | 19 | 293 | 17.7 |
| 30 | 37.2 | 60 | 24 | 289 | 17.2 |
| 40 | 35.9 | 60 | 28 | 295 | 16.5 |

$$\eta = \frac{W_{\text{Turbine}} - W_{\text{Pump}}}{[\text{Geothermal energy absorbed by the working fluid}]} \quad (1)$$

When ammonia is used as a working fluid, the power generated by the ORC increases continuously with increasing working fluid pressure. The efficiency at which it is generated also increases continuously from 12.7% to 23.2% with increasing working fluid pressure. The temperature at which CO₂ leaves the heat exchanger after the transfer of geothermal heat to the working fluid reaches a maximum of 70 °C at a pressure of 2.5 MPa and then decreases to 62 °C with a further increase in working fluid pressure of 4 MPa. When the working fluid pressure exceeds 4 MPa, expansion of the working fluid in the turbine causes condensation. Similarly, when the mass flow rate of the working fluid is beyond 100 kg/s, the heat content of the circulating fluid carrying the geothermal heat is not high enough to convert all the working fluid completely into vapor phase at the outlet of the binary heat exchanger. Therefore, the maximum inlet mass flow rate and the working fluid pressure values are fixed at 100 kg/s and 4 MPa respectively for ammonia.

From Tables 4–6, it can be seen that the mass flow rate of the working fluids *n*-Butane, neopentane and R134A is three times higher than the mass flow rate of ammonia. The range of working

fluid pressures within which the ORC can be operated is substantially higher for these three fluids compared to that with ammonia. Comparing Tables 3–6, it can be seen that in spite of lower working fluid pressures and mass flow rates used for ammonia, the amount of power generated is much higher than that obtained with other working fluids. The lower pump pressure reduces the internal shaft work done on the system and increases the work done by the turbine during expansion, resulting in the highest efficiency for ammonia. The amount of power generated from the ORC for the three working fluids *n*-Butane, Neopentane and R134A is shown in Fig. 3. At all working fluid pressures, the power generated is highest for *n*-Butane and lowest for R134A used as a working fluid. It also shows that there is an optimum working fluid pressure for each one of the three fluids at which the power generated reaches its maximum. The optimum working fluid pressure is 20 MPa for *n*-Butane and 10 MPa for neopentane and R134A. Beyond the optimum, the pump consumes a substantial amount of shaft work generated by the turbine and eliminates the advantage of operating the ORC at higher pressures. It is worth mentioning that when *n*-butane is used as a working fluid, and as the working fluid pressure increases from 15 MPa to 30 MPa, the increase in the amount of power generated in the ORC is less than 0.5 MW.

Table 6
Power output from EGS and efficiency of power generation from EGS for R134A.

| Mass flow rate of working fluid R134A = 100 kg/s | | | | | |
|--|------------------------------------|---------------------------------------|-------------------------------------|------------------------------|------|
| Working fluid pressure (MPa) | Power generated (MW _e) | Exit CO ₂ temperature (°C) | R134A temperature in heat exchanger | | η % |
| | | | <i>T</i> _{in} , °C | <i>T</i> _{out} , °C | |
| 5 | 31.3 | 101 | –26 | 295 | 19.9 |
| 10 | 33 | 110 | –24 | 292 | 22.2 |
| 15 | 32 | 120 | –22 | 284 | 23 |
| 20 | 31.4 | 125 | –21 | 283 | 23.3 |
| 30 | 30.5 | 130 | –17 | 287 | 23.4 |
| 40 | 29.1 | 135 | –14 | 287 | 23.1 |

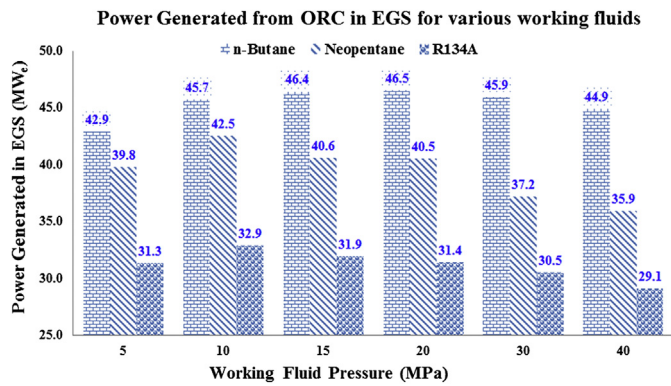


Fig. 3. Comparison of power output from organic Rankine cycle in EGS for various working fluids.

From Tables 4–6, it can be seen that, among the three working fluids *n*-Butane, neopentane and R134A, even though the power generated is lowest for R134A, the efficiency at which it is generated is higher than that for the other two working fluids. Among the two hydrocarbons *n*-Butane and neopentane, the power generated and the corresponding generation efficiency is highest for *n*-Butane and lowest for neopentane. The temperature at which CO₂ leaves the geothermal heater is affected by the thermo-physical properties of the working fluid. From Fig. 4, it can be seen that the temperature at which CO₂ is discharged from the binary heat exchanger is highest for R134A and lowest for *n*-Butane. The lower amount of power generated in the ORC, higher CO₂ discharge temperature from the binary heat exchanger and the potential for ozone depletion makes R134A an unattractive choice for working fluid in the ORC. Due to the absence of ozone depletion potential, lower global warming potential and the non-corrosive nature of hydrocarbons, *n*-Butane and neopentane are more attractive candidates for working fluids in the organic Rankine cycle.

In the second case study, the effect of a recuperator on power generated from EGS was studied for the two working fluids neopentane and *n*-Butane. The pressure of the working fluid at the turbine inlet was 10 MPa for neopentane and 20 MPa for *n*-Butane as the maximum power output was obtained at this pressure for these two fluids. When neopentane is used as a working fluid, the power generated decreases continuously with increasing preheating. As shown in Fig. 5, when neopentane is used as a working fluid, the maximum amount of heat that can be transferred from the hot outgoing vapor leaving the turbine to the cold incoming fluid is about 40% beyond which temperature crossover takes place in the recuperator. Even though the power output decreases continuously with an increasing degree of preheating, it can be seen from Table 7 that the temperature at which CO₂ leaves the

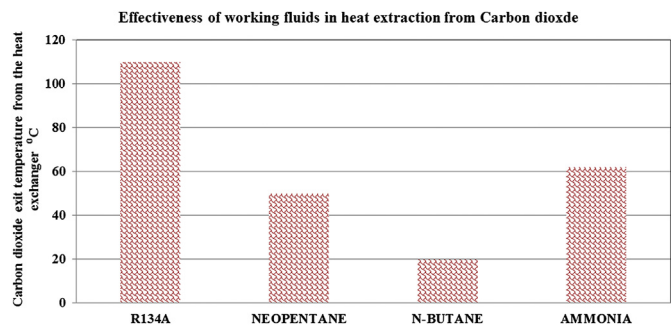


Fig. 4. Comparison of the CO₂ exit temperature leaving the heat exchanger for various working fluids.

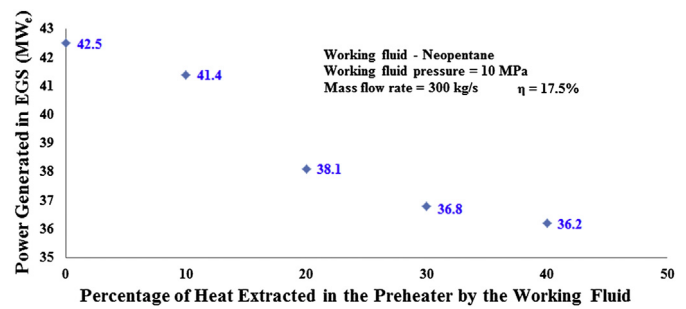


Fig. 5. Variation of power output from EGS for neopentane as a function of preheating.

heat exchanger increases continuously with increasing degree of preheating. This provides an opportunity to add a second ORC so that both the CO₂ and the working fluids can be discharged at the lowest possible temperatures. The temperature at which the working fluid rejects the heat to the condenser decreases continuously with increasing degree of preheating.

When *n*-Butane is used as a working fluid, the variation in power output generated from the ORC and the temperature at which CO₂ is discharged from the geothermal heat exchanger are shown in Fig. 6 and Table 8. As seen in Fig. 6, the maximum amount of heat that can be transferred from the hot vapor leaving the turbine outlet to the cold but high pressure fluid entering the recuperator is 30% beyond that at which temperature crossover takes place. The power generated reaches a maximum when the percentage of heat exchanged is around 10%. The efficiency at which the power is generated is 20.5% when *n*-Butane is used as a working fluid. From Table 8, it can be seen that the temperature at which heat is rejected to the condenser decreases continuously with an increasing amount of heat transferred to the cold high pressure incoming fluid. With increase in the degree of preheating of the high pressure cold working fluid in the recuperator, the temperature at which CO₂ leaves the geothermal heat exchanger increases to 85 °C providing an opportunity to add a second ORC to extract more power so that both the CO₂ and the working fluid can be discharged at the lowest possible temperatures. The work done to recompress 612 kg/s of CO₂ from 12 MPa to 15 MPa is 4.3 MW. The

Table 7

Variation in CO₂ exit temperature with preheating in ORC for neopentane.

| % Preheating | CO ₂ exit temperature, °C | Working fluid reject temperature, °C |
|--------------|--------------------------------------|--------------------------------------|
| 0 | 50 | 183 |
| 10 | 60 | 148 |
| 20 | 80 | 100 |
| 30 | 100 | 62 |
| 40 | 120 | 25 |

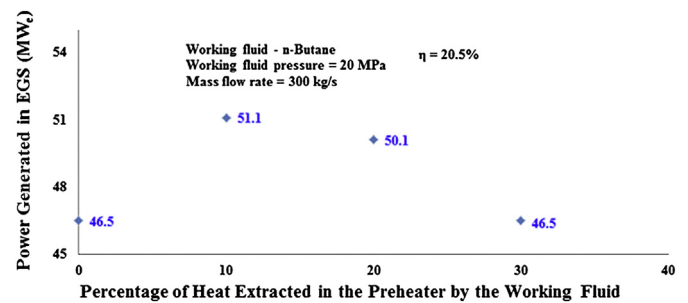


Fig. 6. Variation of power output from EGS for *n*-Butane as a function of preheating.

Table 8
Variation in CO₂ exit temperature with preheating in ORC for *n*-Butane.

| % Preheating | CO ₂ exit temperature, °C | Working fluid reject temperature, °C |
|--------------|--------------------------------------|--------------------------------------|
| 0 | 20 | 118 |
| 10 | 55 | 109 |
| 20 | 65 | 72 |
| 30 | 85 | 23 |

power generated from the EGS in all the cases is substantially sufficient to recover the power lost to recompress CO₂ for subsequent recirculation.

7. Conclusions

Pairing IGCC with EGS, in addition to producing electricity from the organic Rankine cycle, recovers the work done to compress the CO₂ from IGCC for sequestration. This process facilitates the simultaneous sequestration of CO₂ and extraction of geothermal heat and is particularly attractive in arid regions where scarce water need not be expended. Among the four fluids R134A, ammonia, *n*-Butane and neopentane used for process modeling of ORC, the power generated (49 MW_e) and the efficiency (23%) at which it is generated is highest for ammonia. The possible temperature at which CO₂ was discharged from the binary heat exchanger was highest for R134A and lowest for *n*-butane. Considering the corrosive nature of working fluid, ozone depletion potential and greenhouse gas potential, *n*-Butane and neopentane can be considered as the potential candidates for the working fluids in ORC. Addition of the preheater facilitates the extraction of heat from the hot outgoing fluid leaving the turbine so that it rejects its latent heat to the condenser at the lowest possible temperature. The recuperator also gives an opportunity to add a second Rankine cycle so that more power can be generated discharging both the CO₂ and the working fluid at the lowest possible temperatures.

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