MODELLING A COMPLETE CO_2-EGS POWER GENERATION PROCESS

Alvin I. Remoroza[1], Elham Doroodchi[2], and Behdad Moghtaderi[1]

[1]Priority Research Centre for Energy, University of Newcastle, Callaghan, NSW 2308, Australia

[2]Priority Research Centre for Advanced Particle Processing, University of Newcastle, Callaghan, NSW 2308, Australia

Alvin.Remoroza@uon.edu.au

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ABSTRACT

A comprehensive analysis of a CO_2-Engineered Geothermal System (EGS) power plant was compared with a H_2O based EGS with Organic Rankine Cycle (ORC). One, two and three-dimensional reservoir simulations were coupled with 1D wellbore flow to examine the effect of different reservoir and injection parameters such as injection pressure, injection temperature, reservoir depth or pressure, injection-production distance, resource temperature, and others.

The radial reservoir flow model (2D) compared very well with the 3D results using TOUGH2-ECO2N simulator and can be used for rapid assessment of reservoir and injection/production parameters. 3D reservoir simulation is most appropriately used for the detailed analysis of reservoir response to injection/production, i.e. thermal breakthrough and depletion as function of time.

It was found that the CO_2-EGS performance could be optimised (e.g. change injection wellbore diameter) to match or exceed H_2O based EGS at a given reservoir condition. CO_2 mass circulation is higher than H_2O at the same operating and reservoir conditions. The CO_2 heat extraction rate depends both on reservoir pressure and temperature as compared with H_2O which primarily depends on temperature. The CO_2 heat extraction rate is higher at lower reservoir pressure (shallower reservoir depth) but not necessarily at total exergy and electricity generation potential.

Our simulation shows that CO_2-EGS through optimisation of injection and reservoir parameters can stably and sustainably generate 10 MW of electricity per 1 km^2 of a 200^{o}C geothermal resource.

1. INTRODUCTION

The literature on the use of CO_2 as geofluid (i.e. CO_2-thermosiphon) is scarce and is mostly on exergy analyses of CO_2-EGS. The reported heat extraction rates are a good indication of power generation potential but may not be adequate since electricity production is dependent on the temperature, enthalpy, and mass flow rate of the fluids in the wellheads. Temperatures at the wellheads affect the over-all thermal efficiency of a power plant cycle.

Some of the materials published regarding CO_2-thermosiphon, however, showed some inaccuracies. The exergy analysis by (Atrens, Gurgenci, & Rudolph, 2009b) used an incorrect equation for calculating pipe frictional losses.

In other papers (Atrens, Gurgenci, & Rudolph, 2009a, 2010), the change in enthalpy of fluid down the wellbore was calculated from

$\Delta h = g\Delta z - \frac{v^2 \Delta z}{\frac{P}{\rho g} - 2\Delta z}$ and $\Delta h = g\Delta z - \frac{v^2 \Delta z}{2}$, yet one of the assumptions is that there is no heat flow across the boundaries of the wellbore (i.e. adiabatic flow).

From thermodynamics, change in enthalpy is defined as $dH = TdS - VdP$ where $TdS = \partial Q$=heat added to the system in a reversible process, V is volume, and dP is change in pressure. Specific enthalpy can only be uniquely defined by two state variables, e.g. pressure and temperature, pressure and specific entropy, etc.

Very few papers exist in the open literature for 3D CO_2-EGS reservoir simulations. 3D reservoir simulations of EGS with CO_2 as working fluid modelled after the European HDR experiment at Soultz show greater heat extraction rates for CO_2 compared with H_2O. The preferential flow of cold dense CO_2 at the bottom of the reservoir increased thermal depletion over time, thus resulting to accelerated thermal breakthrough which can be avoided by producing at a limited depth interval at the top of the reservoir (Pruess, 2008; Remoroza, Moghtaderi, & Doroodchi, 2010).

In 2010, (Haghshenas Fard, Hooman, & Chua, 2010) ran CFD numerical simulations of CO_2 geothermosiphon predicting reservoir characteristics based on a system of parallel identical ducts (fractures) and concluded that the overall heat transfer coefficient of the reservoir is a function of fluid thermophysical properties, the injection mass flow rate, and the fracture wetted periphery.

Agarwal and Anderson, 2010 compared the net electricity generation of CO_2 and H_2O based EGS using the same mass circulation of both fluids and found that H_2O generates 70-80% more compared with CO_2.

This paper will compare 1D, 2D, and 3D CO_2-EGS reservoir simulation results coupled with 1D wellbore flow. Thermodynamic and power cycle analyses of a CO_2

thermosiphon and a H_2O based EGS will be compared under similar operating conditions.

2. NUMERICAL METHODS

2.1 1D 2D Reservoir Calculations

For 1D coupled reservoir and wellbore flow simulations, an iterative procedure is implemented to solve for the mass circulation flow rate of the fluid by taking into account the mass and energy balances from the top of the injection well to the bottom of the production well (Atrens, et al., 2009b; Remoroza, Moghtaderi, & Doroodchi, 2009). Assumptions include adiabatic wellbore flow and Darcy reservoir flow of constant-cross sectional area defined by impedance parameter kA (Fig 1) with linearly increasing temperature. Mass and energy balances are solved using Engineering Equation Solver (EES). To define the system, reservoir pressure at the bottom of the production well and injection pressure and temperature at the surface are set at the beginning of the calculation, then the mass circulation (injectivity) is iteratively solved.

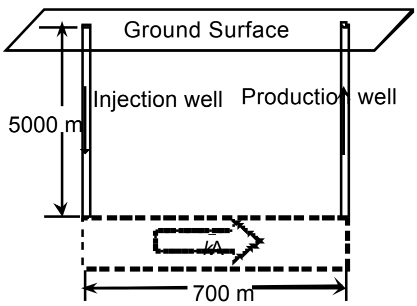

Figure 1: Schematic of a 1D reservoir model.

In the 2D or radial reservoir flow model (Fig 2), pressure distribution in the reservoir from an injection well was described by Remoroza, et al. (2009).

Table 1 lists all the reference data used in 1D and 2D coupled reservoir and wellbore simulations. The results of the calculations from 1D and 2D simulations represent only the steady state flow and therefore a snapshot of the entire reservoir-power production process. Reservoir temperature changes with time as heat is being depleted and will change fluid mass circulation and pressures dynamically.

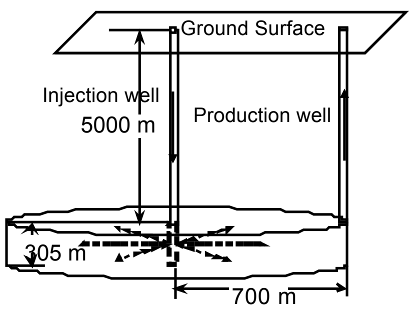

Figure 2: Schematic of a 2D reservoir model.

Table 1: Reference data used in the 1D/ 2D simulations.

Parameter	Values
Reservoir Length	700 and1000 m
Reservoir Temperature	175, 200, 225 and 250 ^{0}C
Injection Temperature	15, 25 and 35^{0}C
kA (inverse impedance)	2.1E^{-9} m^4
Reservoir Pressure, P_{res}	20, 35, and50 MPa
Wellbore Roughness (ε)	40 µm
Wellbore Diameter, D	0.2315 and 0.463 m

2.2 3D Reservoir Simulations

TOUGH2 with ECO2N equation of state module was used in the 3D reservoir simulation. TOUGH2 is a general-purpose numerical simulation program for multi-phase fluid and heat flow in porous and fractured media for applications in geothermal reservoir engineering, nuclear waste disposal, unsaturated zone hydrology, and geologic storage of CO_2 (Pruess, Oldenburg, & Moridis, 1999). ECO2N is a fluid property module for the TOUGH2 simulator (Version 2.0) that was designed for applications to geologic sequestration of CO_2 in saline aquifers (Pruess, 2005). Only all-CO_2 or all- H_2O phase simulations were performed.

To validate the use of ECO2N, the result of previous 3D reservoir simulations performed by (Pruess, 2008) were duplicated using the same set of reservoir and fluid parameters (Remoroza, et al., 2010; Remoroza, Moghtaderi, & Doroodchi, 2011). Pruess (2008) used TOUGH2 with fluid property module "EOSM", which is not publicly or commercially available. His simulations examined production behaviour in a 2D areal model at different reservoir pressures and then assessed 3D flow effects on energy recovery. Our validations showed almost a perfect match to the values obtained by prior studies (Remoroza, et al., 2010, 2011)

The simulations assume an infinitely large geothermal reservoir with 1 km^2 five-spot well configuration and single phase fluid flow (pure CO_2 or pure H_2O). Because of symmetry, the simulations were run on ¼ of the areal coverage, capturing the injection well and 1 production well. The numbers reported in this study, however, are based on a full five-spot well configuration. Table 2 lists the reservoir and other parameters used in the 3D reservoir simulations.

Prior studies have shown that producing from all layers of the CO_2 reservoir causes a rapid thermal decline compared with producing only from the top 50 m layer (Pruess, 2008; Remoroza, et al., 2010). Since it is desirable to have stable production outputs, this study will report CO_2 reservoir simulation results based on the production on the topmost 50 meter layer. In comparison, the 3D reservoir simulation of H_2O-based EGS showed that producing from all layers and from only the top 50 m layer of the reservoir have the same general trend although the latter gives slightly higher heat extraction rates.

Table 2: Reservoir and injection/production parameters used in the 3D simulation runs.

Formation	
Thickness, m	305, 610, 1220
Fracture spacing, m	50
Permeable volume fraction	2%
Permeability in fracture domain, $x10^{-15} m^2$	0.5, 5 and 50
Porosity in fracture domain	50%
Permeability in rock matrix, $x10^{-15} m^2$	0.5, 5 and 50
Porosity in rock matrix	2%
Rock grain density, kg/m^3	2650
Rock specific heat, kJ/kg	1000
Rock thermal conductivity, W/m-°C	2.1
Initial conditions	
Reservoir fluid	CO_2, H_2O
Temperature, °C	175, 200, 225, 250
Pressure, MPa	20, 35, 50
Production/Injection	
Injection Temperature, °C	15, 25, 35
Bottomhole production pressure, MPa	+1 or calculated
Bottomhole injection pressure, MPa	-1 of reservoir pressure

2.3 Power Cycle Calculations

In the CO_2 based EGS power cycle analysis (Fig 3), power is calculated as the change in fluid enthalpy across the turbine (assumes 85% efficiency and CO_2 directly drives the turbine blades).

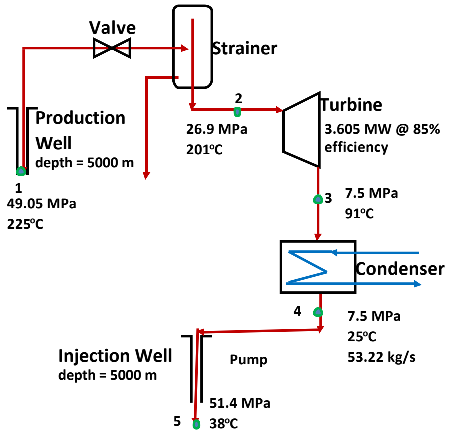

Figure 3: Schematic of a CO_2-EGS power cycle.

In H_2O based EGS with ORC (Fig 4), thermal energy is transferred from hot H_2O to a secondary fluid which in turn produces work via isentropic expansion in the turbine. In this binary system, H_2O is not directly used to drive the turbine. Instead, a secondary fluid is heated and vaporised to drive the turbine. A circulating pump is used to pump the secondary fluid to the desired inlet turbine pressure. The system is complex compared with the CO_2-EGS power cycle.

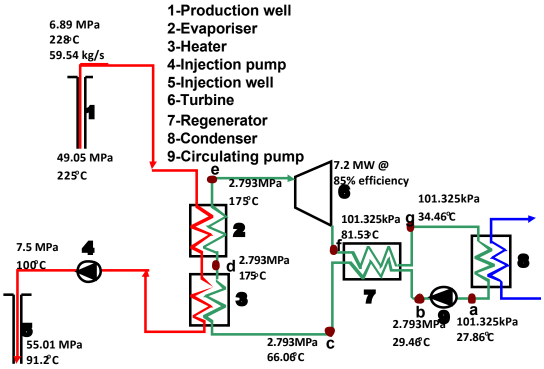

Figure 4: Schematic of a binary ORC for H_2O-EGS.

We assume the use of isopentane as the secondary fluid with circulating pump pressure of 2.793 MPa (T_{sat} = 175 ^{0}C) and condenser pressure of 101.325 kPa (atmospheric condition). This circulation pump pressure is chosen so that the existence of a two-phase fluid is avoided during expansion at the turbine while giving the maximum power. Pump efficiency is assumed to be 75% and undergoes isentropic process. The circulating mass flow rate of isopentane and the power generated from the turbine were determined by solving simultaneously mass and energy balance around the binary cycle system Heat input to the system is equal to the change in enthalpy of H_2O between the production and injection wells. The designed minimum pinch or the temperature difference between the counter-flowing fluids in heat exchangers is 5 ^{0}C.

The net power generated from H_2O based EGS with ORC is calculated as turbine power minus pump power for H_2O injection and pump power for circulation of the secondary working fluid.

$$W_{net} = W_{turbine} - W_{pump,injection} - W_{pump,circulation}$$

The net electrical power is the optimum solution computed using EES based on production pressure and temperature and rejection temperature and therefore will not necessarily reject H_2O at any set injection temperature. In this case, it is assumed that the rejected H_2O from the binary plant is further used for other purposes that will reduce its temperature to the set injection temperature.

In both CO_2 and H_2O based EGS, power losses in the cooling tower and other parasitic losses (assumed similar for both CO_2 and H_2O based EGS) are neglected in the calculation of net power generation.

3. RESULTS AND DISCUSSION

The number of dimensions used in numerical simulation usually increases complexities and simulation times. Although three and higher dimensional analyses are required for detailed, accurate, and realistic simulations, it requires complex programming and most often leads to acquisition of highly specialised third-party software like TOUGH2, FLUENT for CFD, and others. However, for rapid and approximate assessment of a model, 1D or 2D analysis may suffice for initial evaluation.

Figures 5 and 6 show that 3D and 2D CO_2 reservoir simulations agree very well in mass flow and heat extraction rates, respectively. Figure 7 shows the result of the CO_2 reservoir 3D analysis with time which shows a relatively stable flow. The initial conditions used in the simulations are 25 °C wellhead injection temperature, 200 °C reservoir temperature, 49 MPa production well bottomhole pressure, and 5000 m well depth. In the 3D reservoir simulation, the initial condition is 35 °C bottomhole injection temperature, which approximately translates to 25 °C wellhead injection temperature.

The effect of CO_2 surface injection temperature is shown in Fig 8. The mass circulation and heat extraction rates are inversely related to CO_2 injection temperature. The optimum electricity generation varies with injection temperature and injection pressure:12 MW at 9.5 MPa, 9.9 MW at 11.5 MPa, and 9 MW at 13.5 MPa injection pressures for 15, 25, and 35 °C injection temperature, respectively (Fig 9). The reservoir condition is at 200 °C and 50 MPa.

Reservoir pressure greatly affects CO_2 mass circulation and heat extraction rates (Figure 10). The results show that the performance of CO_2 EGS is better at a shallower reservoir (Pruess, 2008; Remoroza, et al., 2009) and lower injection pressure is required for similar optimum electricity generation (Fig 11). At 20 MPa reservoir pressure, the optimum electricity is ~9.6 MW at 7.5 MPa injection pressure. The results can be explained by CO_2 specific enthalpy behaviour, which is greatly affected by temperature and pressure. The P-h diagram of CO_2 (Fig 12) shows that the specific enthalpy increases significantly with decreasing reservoir pressure.

Reservoir temperature does not significantly affect CO_2 mass circulation rates but increases heat extraction rates because of higher specific enthalpy at higher temperature (Fig 13). Consequently, exergy and electricity generation also increase with reservoir temperature (Fig 14).

Reservoir thickness increases CO_2 mass flow and heat extraction rates. Doubling the thickness increases the optimum electricity generation by 12.5%, and quadrupling the thickness increases the optimum electricity generation by 20% (Fig 15). In real systems, it should be noted that the actual thickness of the reservoir that will be accessible for heat mining will be limited to the effectiveness of the stimulation used and the characteristic of the reservoir itself.

Doubling the injection well diameter while keeping production well diameter the same significantly improves mass circulation and heat extraction rates and consequently improves optimum total exergy and electricity generation (Fig 16). The mass circulation approximately doubles, and the optimum electricity generation increases from 9.6 MW (at 7.5 MPa injection pressure) to 17.3 MW (at 6.75 MPa injection pressure).

Comparing CO_2 and H_2O based EGS, the CO_2 mass circulations are higher (Fig 17), but the CO_2 total exergies are lower compared with H_2O based EGS (Fig 18). The electricity generation of H_2O based EGS increases linearly with increasing injection pressure while CO_2 EGS shows a parabolic trend. CO_2 EGS optimum electricity is 9.6 MW at 7.5 MPa injection pressure compared with 13.2 MW for H_2O at the same injection pressure.

However, doubling the injection well diameter approximately doubles CO_2 mass circulation rates while H_2O only increases by approximately 20%. The optimum electricity generation of CO_2 EGS increases to 17.3 MW at 6.75 MPa injection pressure compared with ~14 MW for H_2O based EGS (Fig 19). This can be explained by looking at the frictional and reservoir losses of both systems. CO_2 has higher frictional losses than H_2O (i.e. CO_2 losses 620 Pa/(kg/s) compared with 145 Pa/(kg/s) for H_2O at 7.5 injection pressure). The higher overall frictional losses of CO_2 are mainly due to higher mass flow and lower density compared with H_2O.

On the other hand, H_2O reservoir pressure losses are higher at 61. 6 kPa/(kg/s) compared with 7.77 kPa/(kg/s) for CO_2 at 7.5 injection pressure. This is due to H_2O's higher kinematic viscosity (ratio of absolute viscosity and density) at reservoir conditions. At 200 °C and 20 MPa, kinematic viscosity of H_2O is 1.581×10^{-7} m²/s and CO_2 is 1.111×10^{-7} m²/s. Also, H_2O's kinematic viscosity increases at lower temperature conditions while CO_2's decreases, i.e. at 25 °C and 20 MPa H_2O has 8.817×10^{-7} m²/s compared with CO_2 which only has 1.039×10^{-7} m²/s.

The overall results imply that CO_2 EGS performance can be optimised to match the performance of H_2O based EGS at a given reservoir condition.

The 3D reservoir performance of CO_2 based EGS was investigated using two simulated scenarios. The first scenario used a constant injection mass flowrate of 252 kg CO_2 /s obtained from 2D simulation where the injection and production well diameters are the same, and the second used 444 kg CO_2/s mass flow obtained from the 2D simulation where the injection well diameter is twice that of the production well.

The heat extraction rates at 252 kg/s injection is fairly stable for 20 years, dropping only 4 MW from 87 to 83 MW and steadily declining to 58 MW after 35 years. The 444 kg/s injection rate is extracting heat stably for only 10 years, dropping 5 MW from 150 to 145 MW but sharply declining to 47 MW after 35 years (Fig 20). Electricity generation at 252 kg/s injection is fairly stable for 20 years with an average of 9.5 MW and then declines to 5.3 MW after 35 years. On the other hand, the 444 kg/s injection rate is stable at an average of 17.8 MW electricity generation for 10 years and then sharply drops to 2.2 MW after 35 years (Fig 21).

The results imply that one can find optimum CO_2 injection rates for a given allowable decline rate within a period of time and/or the most economical well diameter since CO_2 injection rate will dictate the size of the injection well and surface facilities (and the corresponding capital investment cost).

Based on our simulation, CO_2 EGS through the optimisation of injection and reservoir parameters can stably generate 10 MW of electricity per 1 km^2 of 200 °C geothermal resource with at least 305 meter thickness. Therefore, generating 1 GW of electricity would roughly require 100 km^2 (10 x 10 km).

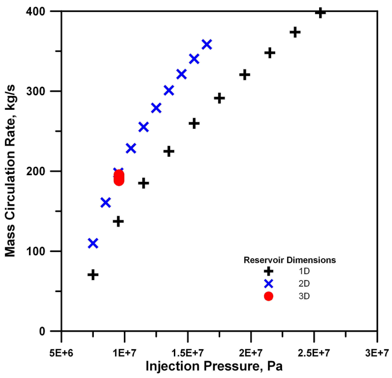

Figure 5: CO_2 mass circulation rates at different dimensional analysis.

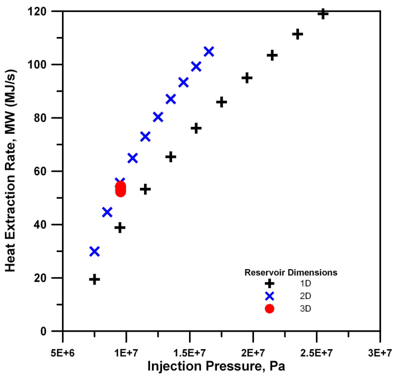

Figure 6: CO_2 heat extraction rates at different dimensional analysis.

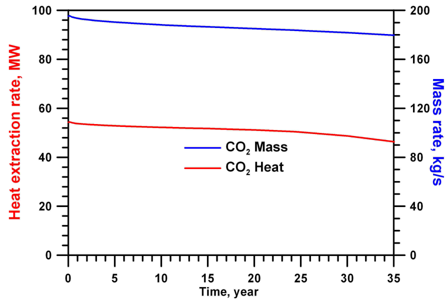

Figure 7: CO_2 mass production and heat extraction rates as function of time from the 3D analysis.

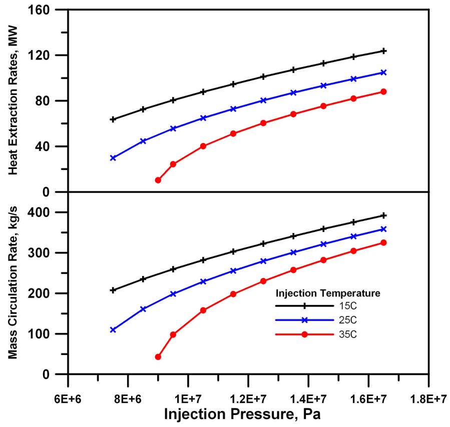

Figure 8: Effect of CO_2 injection temperature on mass production and heat extraction rates.

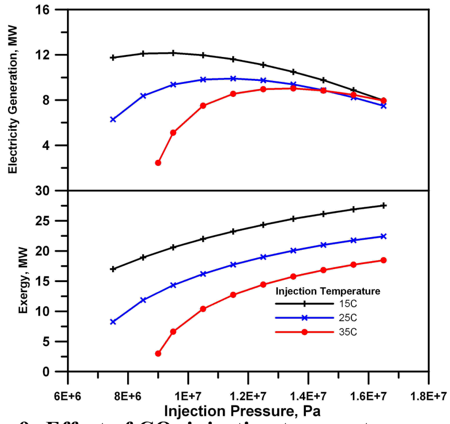

Figure 9: Effect of CO_2 injection temperature on exergy (bottom) and electricity generation (top).

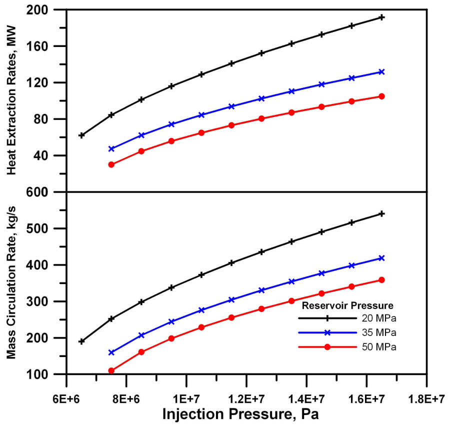

Figure 10: CO_2 mass and heat extraction rates at different reservoir pressure.

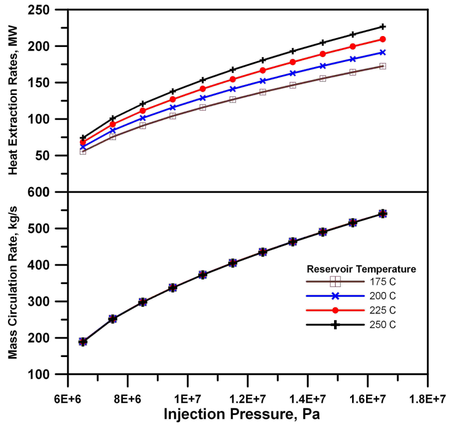

Figure 13: CO_2 mass and heat extraction rates at different reservoir temperature.

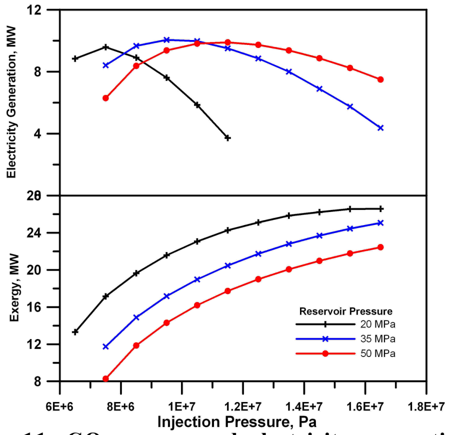

Figure 11: CO_2 exergy and electricity generation at different reservoir pressure.

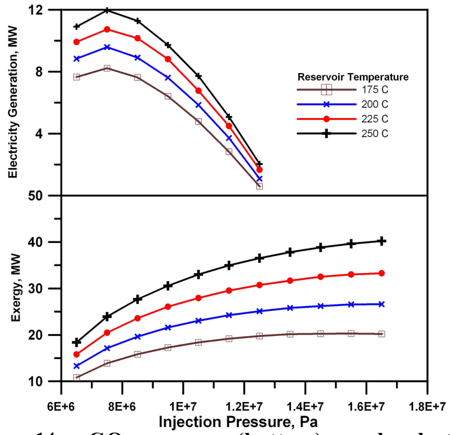

Figure 14: CO_2 exergy (bottom) and electricity generation (top) at different reservoir temperature.

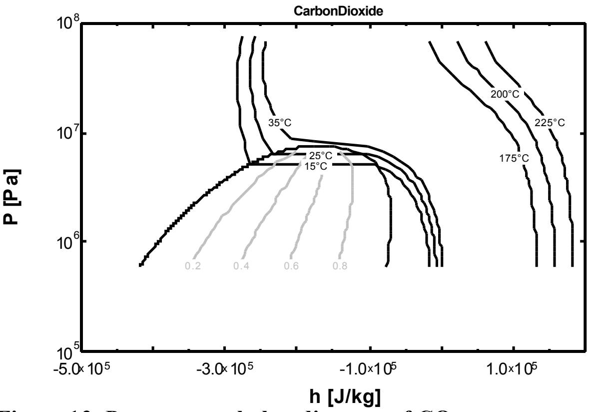

Figure 12: Pressure- enthalpy diagram of CO_2.

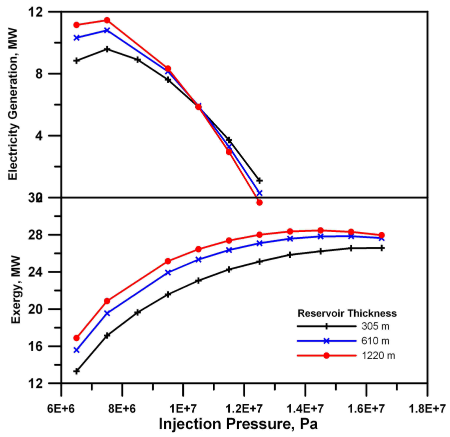

Figure 15: Effect of reservoir thickness on CO_2 exergy and electricity generation.

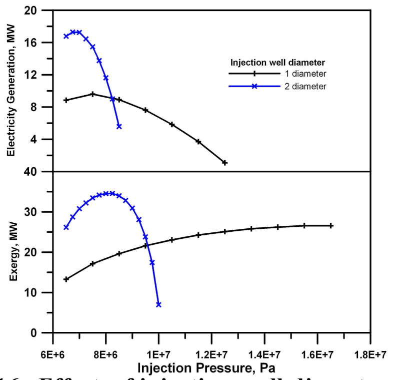

Figure 16: Effect of injection well diameter on CO_2 exergy and electricity generation.

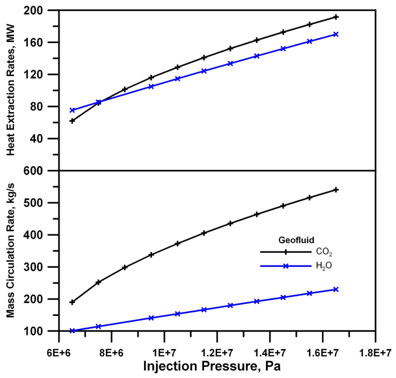

Figure 17: Mass and heat extraction rates of H_2O and CO_2 based EGS.

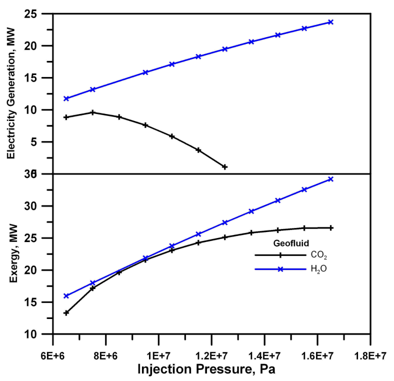

Figure 18: Exergy and electricity generation of H_2O and CO_2 based EGS under similar reservoir and injection conditions.

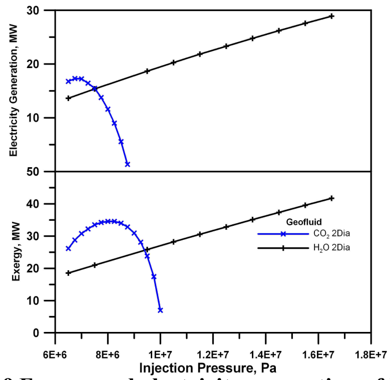

Figure 19 Exergy and electricity generation of H_2O and CO_2 based EGS after doubling injection well diameter.

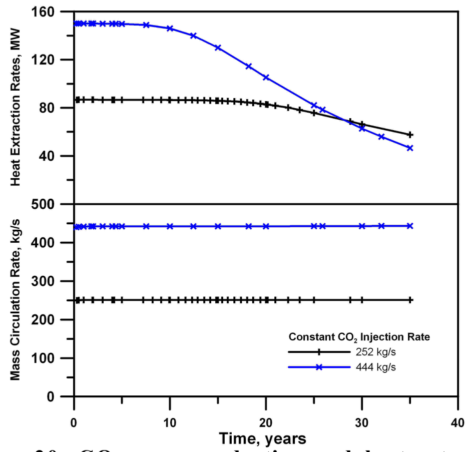

Figure 20: CO_2 mass production and heat extraction rates at different constant mass CO_2 injection.

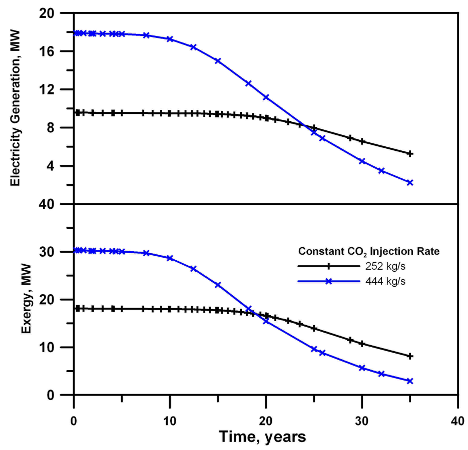

Figure 21: exergy and electricity generation at different constant mass CO_2 injection.

4. CONCLUSIONS AND RECOMMENDATION

The results show that the 2D reservoir flow (radial flow) compares very well with the 3D simulation using TOUGH2-ECO2N simulator. Coupled 1D wellbore and 2D reservoir flow simulations can be used for rapid assessment of reservoir and injection/production parameters while the 3D reservoir simulation is most appropriately used for detailed analysis of reservoir response to injection/production (.e. thermal breakthrough and depletion as function of time).

The results of the simulation show that given the same reservoir temperature, heat mining using CO_2 at lowest possible reservoir pressure (shallower depth) is desirable because CO_2 specific enthalpy is higher at low pressures (so that more heat can transfer from the rock to the fluid). CO_2 specific enthalpy increases with temperature, so it follows that a higher reservoir temperature increases heat extraction rates and consequently electricity generation. CO_2 injection temperature decreases the overall electricity generation while injection pressure generally increases mass circulation, but electricity generation shows a parabolic trend (i.e. there exists an optimum injection pressure beyond and below which the electricity generation will decrease).

Injection well diameter greatly affects CO_2 mass circulation. Doubling the well diameter almost doubles the CO_2 mass circulation. In comparison, H_2O mass circulation only increases by ~20% when the injection well diameter is doubled.

Reservoir pressure losses of H_2O are higher than CO_2 because of H_2O's higher kinematic viscosity at reservoir conditions. Well frictional losses of CO_2 based EGS are higher because of higher mass flow rates and lower densities of CO_2 compared with H_2O at the same temperature-pressure range.

Injection-production horizontal distance does not significantly affect CO_2 mass circulation given that the optimum mass circulation at a given injection and reservoir condition (injection pressure, well diameter, reservoir pressure and temperature, etc.) has already been achieved. Doubling reservoir thickness increases the optimum electricity generation by 12.5%, and quadrupling increases it by 20%. A thicker reservoir also means a higher mineable geoheat content, but it also depends on the efficiency o fthe reservoir stimulation.

Other areas of research that need to be done for CO_2 EGS include CO_2-rock geochemical interactions, CO_2-well cement reaction, CO_2-H_2O-carbon steel reaction, CO_2 turbine, and others.

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