Pairing of an Integrated Gasification Combined Cycle Power Plant (IGCC) with CO_2-EGS as a Strategy for Deployment in Arid Regions

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ABSTRACT

We explore the utility of linking an integrated gasification combined cycle (IGCC) plant with EGS. The principal attributes for this linkage is that the IGCC system generates electricity with most of the waste streams reused in the overall process and that the primary output is a stream of pure CO_2 that may be used directly as a heat transfer fluid. This CO_2 may be used either in EGS or as a sequestration stream into a porous aquifer with additional scavenging of heat.

We explore the major components of the IGCC system related to coupling with fluid circulation within a geothermal reservoir. The principal features are that combustion of coal using oxygen (rather than air) produces an output stream of H_20 and CO that may be converted to H_2 and CO_2. The hydrogen is available for combustion or higher-value uses and the pure stream of CO_2 reduces the aquifer storage space for sequestration or may be used, as in this case, as a supply stream for EGS. In this case, thermal energy from the EGS reservoir is converted to electricity, as is the steam from the combustion of hydrogen.

The IGCC system integrates the combustion of coal with generation of electricity through a steam turbine and importantly with a concentrated output stream of CO_2 alone. This may be used for direct injection of CO_2 into the subsurface – either for sequestration in a porous aquifer or to develop a low fracture porosity EGS reservoir. In this application we concentrate on the latter, identifying the principal attributes of performance of such a system. We note the favorable to neutral heat transfer and fluid transport characteristics of CO_2 relative to water and how these impact the operational feasibility of such as system. We examine the role of fluid rock interactions as the reservoir is developed and as the CO_2 displaces a water front toward the periphery of the effective reservoir. Similarly, we examine the role of these effects on rates of reservoir development and on permeability evolution and on triggered seismicity.

Finally, we examine the thermal output from various reservoir geometries from longitudinal to five-spot patterns and scale the necessary linkage between CO_2 output from the IGCC plant to the needs of the geothermal system, inclusive of projected fluid losses to the periphery. These discussions are relevant to the feasibility for commercialization of such linked models of IGCC and EGS.

Introduction

The world's growing demand for energy is accentuated by societal desires that it be cheap, clean, secure, and low-carbon. It is unlikely that a single existing or emerging energy resource can effectively accommodate all those demands. A more plausible scenario toward meeting global energy demand is a diversified mix of energy technologies utilizing both renewables and fossil fuels. This could include complex but creative energy plants that combine renewables and fossil fuels to enable the economical production of plentiful power while eliminating or reducing carbon emissions. One such novel configuration is the subject of this paper.

Specifically, this study proposes a power plant combining two energy technologies: Enhanced Geothermal Systems (EGS) and Integrated Gasification Combined Cycle (IGCC). Such a combination would have multiple advantages, including: (1) Use of the IGCC plant's effluent CO_2 stream as a heat transfer fluid in EGS, (2) Sequester CO_2, (3) Minimize water use, (4) Reduce carbon footprint, and (5) Expand geographical and commercial relevance of both technologies.

We are currently studying the technical and economic feasibility of such a technology pairing. This paper describes initial results from our on-going work. Specifically, we will discuss the individual technologies, our proposed concept, potential process configurations, key technical metrics, and their impact on levelized costs of electricity (LCOE).

Technology Descriptions

Geothermal energy utilization can be significantly enhanced by EGS. Enhanced Geothermal Systems are engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources. Geothermal energy from EGS represents a large, indigenous resource that can provide base-load electric power and heat at a level that can have a major impact on the United States, while incurring minimal environmental impacts.

An Integrated Gasification Combined Cycle (IGCC) plant uses a gasifier to convert coal (as well as other fuels such as biomass) in to synthesis gas followed by the use of a combined cycle power plant to generate electricity. The IGCC technology offers a number of advantages, including higher efficiency, a pure effluent stream of carbon dioxide (CO_2) enabling carbon capture and sequestration (CCS), lower water use, and reduced solid waste.

Conventional deployment of EGS has focused on the use of water as a heat transfer fluid. Water's many technical advantages are being overshadowed because (1) it is becoming increasingly scarce, especially in arid areas where EGS enjoys better technical viability, (2) its industrial use directly competes with its demand for human survival, and (3) its excellent solvent properties lead to dissolution, precipitation, and scaling effects.

Given these issues and the growing demand to reduce atmospheric CO_2 levels, Brown[1] proposed the use of CO_2 as a heat transfer fluid in EGS plants. Such a solution would not only replace water as a heat transfer fluid but also enable sequestration of CO_2thereby reducing its atmospheric levels. Carbon dioxide has several physical and chemical properties that favor the technical feasibility of such an idea, including: (1) large expansibility creating sufficient density differentials and therefore buoyancy between cold and hot CO_2streams and reducing parasitic power consumption required for pump the heat transfer media; (2) lower viscosity leading to higher flow rates at a given pressure gradient; (3) poor solvent for rock minerals thereby reducing dissolution, precipitation, and scaling issues.[2]

Several other advantages have also been presented in literature. For example, Fouillac et al.[3] suggest favorable geochemical properties with using $CO_2$for EGS, while Pruess[2]has shown that $CO_2$is quite similar in heat transfer properties to water. There is, however, one major disadvantage: CO_2has lower heat capacity in comparison to water but higher flow rates can be used as a compensating factor.

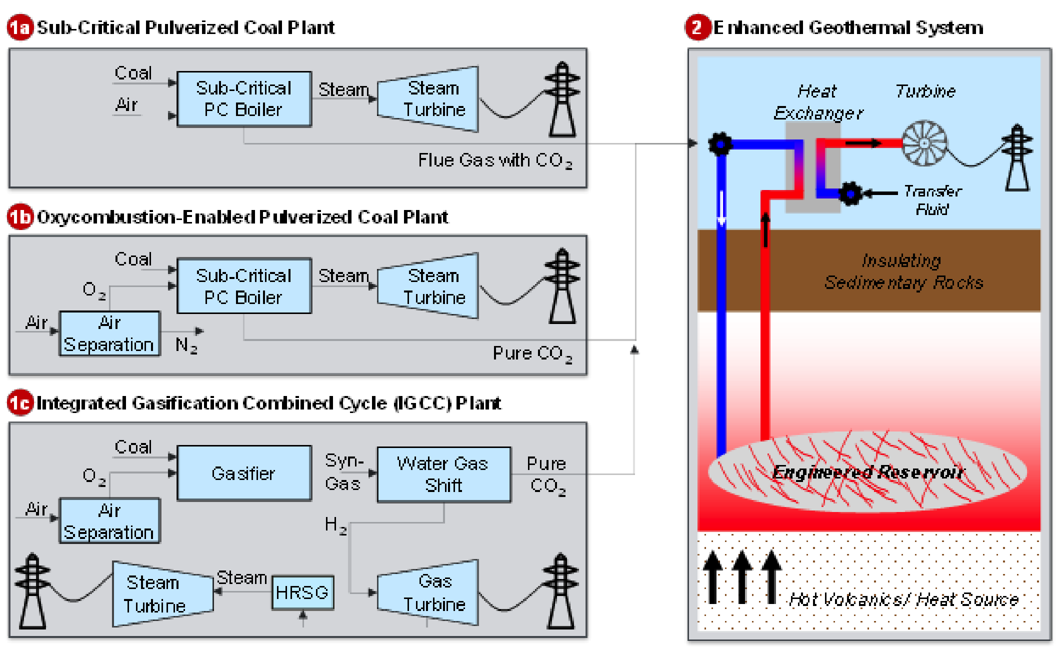
In the gasification process, a solid carbonaceous feedstock is converted to gaseous feedstock. The gaseous fuel retains approximately 75% to 90% of the heating value of the solid carbonaceous feedstock.[4] Combining the Brayton cycle and the Rankine cycle together increases the efficiency of the IGCC process to 38.4% based on higher heating value without carbon capture and sequestration. Pre-combustion carbon capture is the preferred method for carbon capture for IGCC as the pure carbon dioxide stream is readily available for sequestration. The efficiency of the IGCC process with carbon capture and storage (CCS) decreases to 31.2% based on higher heating value.[5]

To reduce the efficiency loss due to CCS, the pressurized carbon dioxide can be sent into fractured wells to extract the geothermal energy that is available in the arid areas in the south west part of the United States. Transferring the thermal energy from the supercritical carbon dioxide to another organic fluid to utilize the geothermal energy can recover some of energy lost during carbon dioxide capture and storage. In this process, a portion of the pressurized carbon dioxide flushed into the well to recover the geothermal energy is sequestered due to the leaks through fractures on the rocks in the wells. Rest of the pressurized gas is circulated through the well. The make-up carbon dioxide needed to compensate for the leaks during the geothermal heat recovery process should come from an IGCC plant that is located in the arid areas in the southwest regions of the United States.

Potential IGCC-EGS Configurations

There are three configurations that can utilize the geothermal energy. In the first configuration shown in Figure 1a, coal is burnt completely through combustion with air. The steam generated at a pressure of 16.2 MPa and 538 °C is fed to the steam turbine for expansion through the Rankine cycle. The flue gas at atmospheric pressure containing carbon dioxide that is diluted mainly in nitrogen is fed into the fractured well to extract the geothermal heat as shown in Figure 2 and transfer the geothermal energy into another heat transfer fluid in a heat exchanger. Expansion of the heat transfer fluid through the turbine produces additional power output.

In the second configuration shown in Figure 1b, instead of feeding air to the combustor, oxygen is separated from air in an air separation unit. The oxygen-rich stream is fed to the combustor of a sub-critical coal fired boiler. The steam generated expands through the steam turbine to produce power output. The concen-



Figures 1 and 2. Potential IGCC-EGS configurations.

trated carbon dioxide stream is fed into the geothermal well for heat removal. As the specific heat capacity for carbon dioxide is 1.3 times greater than the specific heat capacity of nitrogen, the flue gas from an oxy-coal combustion boiler can extract more heat from the geothermal reservoir. This may also cause the well to dry down pretty soon.

In the third configuration shown in Figure 1c, oxygen blown gasification process is conducted to produce synthesis gas which is a mixture of carbon monoxide and hydrogen. The water gas shift reactor separates the carbon dioxide from hydrogen. Combustion of hydrogen in the gas turbine produces the electric power output. Nitrogen is blend with hydrogen to reduce the adiabatic flame temperature of the working fluid. The heat content from the exhaust of a gas turbine is recovered by the generation of steam in a heat recovery steam generator. The steam produced expands through the steam turbine to produce power output. Carbon dioxide stream separated from hydrogen through Selexol process is injected into the fractured well to extract the geothermal heat. The heat is transferred to an organic fluid in a heat exchanger. Once the heat is exchanged, the carbon dioxide is circulated back into the well. The make-up carbon dioxide needed for the compensation of leaks comes from the IGCC plant.

EGS Implications

A variety of issues relate specifically to interfacing sCO_2-EGS with IGCC. These include all the reservoir interaction behaviors important in ensuring the viability of EGS: viz. reservoir stimulation and development concurrent with developing heat-transfer area within the reservoir. For sCO_2-EGS these include the important and poorly defined role of fluid-rock interactions and their impact on permeability, heat-transfer area and strength characteristics of the reservoir. The latter is ultimately related to production-induced seismicity and the related development of permeability by hydroshears.

Although these issues are crucial and relate fundamentally to the viability of sCO_2-EGS they are beyond the scope of this work. Here we limit ourselves to the highest-level linkages between sCO_2-EGS and IGCC – these relate to anticipated thermal output from such a system and mechanism of interfacing the output stream with IGCC via surface plant. We discuss only the issue of thermal output in the following in particular related to anticipated thermal drawdown within the reservoir. This analysis relies on the selection of (i) an appropriate reservoir configuration and (ii) appropriate mechanistic models for thermal drawdown.

Reservoir Configurations

A variety of potential configurations exist for reservoir development. For the demonstration-level projects currently observed, these configuration have typically been a doublet (single injector and producer) or flanked doublet (single injector flanked by dual producers split from a single surface hole). This configuration is peculiar to demonstration projects as it provides the most effective and lowest-cost access to a deep reservoir. However, for large-scale development, this configuration is likely to be supplanted by other well configurations as shown in Figure 3. Typical within the petroleum field is the repeating "five-spot" pattern.[6] This regular grid is common in shallow regular reservoirs but is disadvantaged where the reservoir is deep as it requires multiple deep wells to access the reservoir zone. Alternative configurations are to examine vertically stacked reservoirs[7] or horizontally aligned reservoirs, now feasible with advances in horizontal drilling technology. It is not clear whether drilling technology in hard rocks is sufficiently advanced to allow the latter.

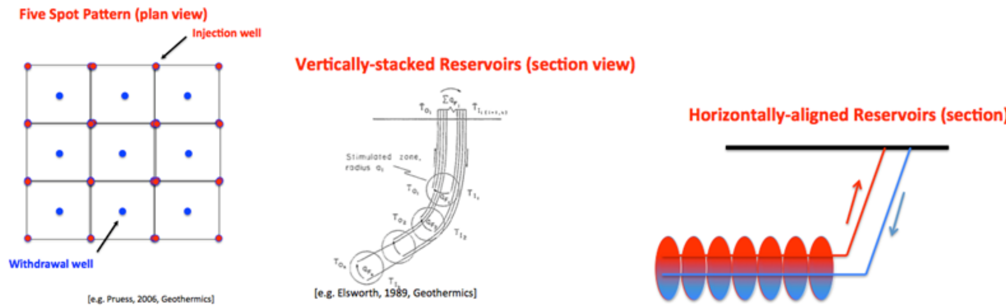


Figure 3. Five spot, and vertically and horizontally stacked reservoir configurations.

Thermal Drawdown Analysis

Somewhat independent of the well configuration thermal drawdown within the reservoir may be evaluated with knowledge of the thermophysical properties of the reservoir rocks and circulated fluid and the geometry of the transport connections within the reservoir. For first order analysis spherical reservoir and parallel flow models are reasonable candidates to represent behavior (Figure 4). The spherical reservoir model (SRM) assumes that both the reservoir and circulated fluids are at thermal equilibrium with temperatures augmented by heat supply from the far-field by conduction.[8] This model gives adequate estimates for heat supply where fracture spacing within the reservoir is small but overestimates thermal output where spacing is large. Where fracture spacing is large the parallel fracture model (PFM) provides better estimates of thermal output and of thermal drawdown although the boundary of the reservoir is assumed thermally isolated and no supplemental heat supply is possible.[9] In practice this latter constraint is of second-order importance and thermal drawdown may be evaluated from knowledge of the previous thermophysical properties supplemented by reservoir volume, fracture

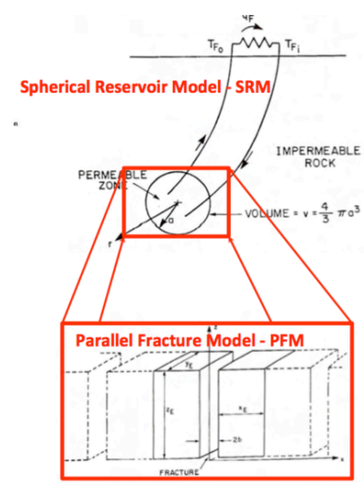


Figure 4. Spherical reservoir (SRM) and parallel fracture (PFM) models for deep EGS reservoirs.

spacing and fluid throughput.[10]

The appropriate thermo-physical properties for the reservoir and fluids are given in Table 1. The non-dimensional thermal drawdown (T_D) scales with three other non-dimensional parameters of flow rate (Q_D), time (t_D) and fracture spacing (x_D). These are:

$$T_D = \frac{T_{Fi} - T_{Fo}}{T_{Fi} - T_R}; Q_D = \frac{q_F \rho_F c_F}{\lambda_R a}; t_D = \frac{\lambda_R t}{\rho_R c_R a^2}; x_D = \frac{x_E}{a}$$

where subscripts are for fluid (F) and rock (R), reservoir inlet (i) and outlet (r), flow rate (q), density (rho), specific heat capacity (c), thermal conductivity (lambda), reservoir radius (a), fracture spacing (x_E) and time (t).

Where the thermophysical parameters of Table 1 are used,

Table 1. Thermophysical material parameters appropriate for sCO2-EGS reservoir modeling.

Property	Rock	Water	CO_2 (200C)	Units
Thermal Conductivity	2.1	0.6	0.015	W/m.K
Density	2600	1000	231	kg/m^3
Specific Heat Capacity	1000	4181	1364	J/kg.K
Thermal Diffusivity	8.1E-07	1.4E-07	4.8E-08	m^2/s

the thermal drawdown of candidate sCO_2-EGS reservoirs may be evaluated. We assume doublet well spacing of 500m as a reasonable candidate separation, fracture spacing in the range 10-100m and fluid circulation rates of 100 and 1000 kg/s of sCO_2. The resulting rates of thermal drawdown are shown in Figure 5 for the SRM and PFM models.

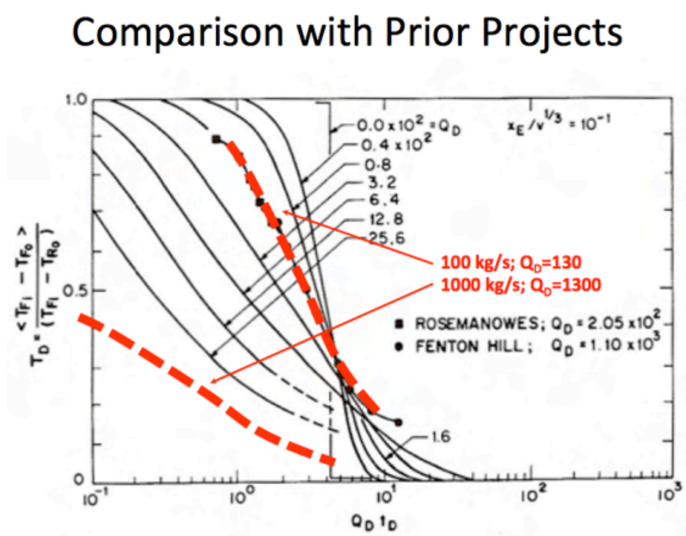


Figure 6. Scaled rates of drawdown for recovery at 1000 and 100 kg/s for the prototypical reservoirs considered here and for prior demonstration projects at Fenton Hill (USA) and at Rosemanowes (UK).[11]

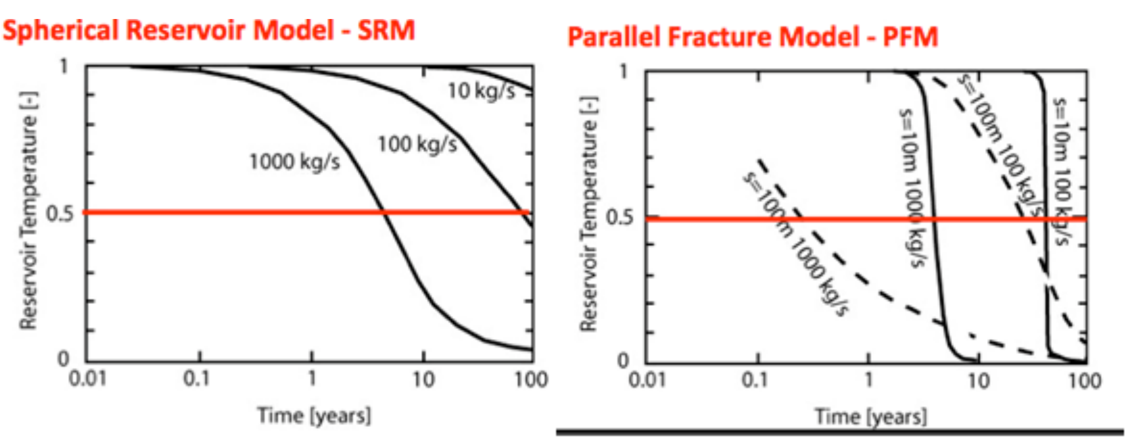


Figure 5. Thermal drawdown (TD) with time for sCO_2 circulation at rates of 100 and 1000 kg/s for fracture spacing within the reservoir of 10m and 100m. Reservoir is 0.125 km^3.

Thermal Drawdown in Prototypical Reservoir

Thermal drawdown within the PFM occurs most rapidly for circulation at 1000 kg/s. Where the fractures are widely spaced (100 m) thermal supply to the circulating fluid is conduction-limited and the reservoir cools rapidly - the reservoir lifetime is of the order of months. Reservoir lifetime is extended for more narrowly spaced fractures and the reservoir approaches a condition of being flowrate limited as evident in the steep decline curve of Figure 5. In this configuration, the thermal drawdown is similar to that of the SRM as in each instance the fluid and average rock temperatures are in equilibrium. However, at this rate of circulation the thermal drawdown is still too severe to be commercially viable limiting the reservoir lifetime to only a few years. However the reservoir lifetime is extended where the circulation rate is reduced. Where the circulation rate is reduced to 100 kg/s the reservoir approaches a state of thermal equilibrium even for widely spaced fractures (100m) and reservoir lifetimes (50% drawdown) are congruent for SRM and PFM as of the order of 20-50y. Thus, limiting rates of circulation (100 kg/s), reservoir volumes (one-eighth of a cubic kilometer) and fracture spacing (<100m) are defined as feasible for reservoir lifetimes of the order of 30 years.

These estimates are consistent with observations scaled from other demonstration projects, most notably the drawdown rates observed at Fenton Hill (USA) and at Rosemanowes (UK) as illustrated in Figure 6.

Thermal Output

With feasible limits placed on circulation rates to ensure a long-lived reservoir, the thermal output may be straightforwardly evaluated from the product of mass flowrate, injection-to-withdrawal temperature differential and specific heat of the working fluid. Thus, the thermal output (W_{th}) is defined as

$$W_{th} = q_F \rho_F (T_{Fi} - T_{Fo}) c_F$$

where all terms are as defined below. Since the IGCC plant is merely supplying the make-up CO_2 to replace leak-off losses, then

Table 2. Comparison of electrical and thermal outputs from a combined sCO_2-EGS-IGCC plant.

Configuration	Coal Output, MW	Thermal Efficiency	CO_2 Flow Rate, kg/s	EGS Output, MW	CO_2 Leakoff
Sub-Critical PC	315	34%	82	179	10%
IGCC	315	42%	69	150	10%
Oxycombustion PC	315	34%	82	179	10%

the circulation rate of the sCO_2-EGS system is in direct proportion to the make-up volume rate. For presumed losses of 5%-10% the ultimate reservoir circulation volumes are in the proportion of 20-10 times the IGCC output rates, respectively. Thus IGCC-CO_2 production rates of the order of 80 kg/s (Table 2) translate to sCO_2-EGS circulation rates of the order of 800 kg/s (10% loss) to 1600 kg/s (5%). For a presumed reservoir temperature of 200°C and a reinjection temperature of 40°C the thermal drop across the system is 160°C. This results in an augmented upper bound (geo)thermal output of ~180MW_{th} to supplement the 315 MW_e from the IGCC.

Cost Impacts

We began our economic analysis by first studying the cost impact of CO_2 as heat transmission fluid on levelized cost of electricity (LCOE) from an EGS plant. Estimates for LCOE were derived using cost and performance correlations embedded in the Geothermal Electric Technologies Evaluation Model (GETEM), a tool used by the U.S. Department of Energy. Figure 7 shows the impact on LCOE in deep EGS scenario while similar effect was observed in near-field EGS scenario as shown in Figure 8.

The first and the foremost effect of use of CO_2would be reduction in the use of water as a geofluid, water losses during injection and make up water requirements. This reduction in water requirement was used for estimating the reduction in LCOE. Unlike water, density of carbon dioxide changes significantly with temperature creating a large density difference between hot and cold carbon dioxide. The resulting thermal siphoning would significantly reduce the circulating pumping power. This effect was simulated in the model considering the lower parasitic losses. Some adjustments were done for no scaling because of the lower

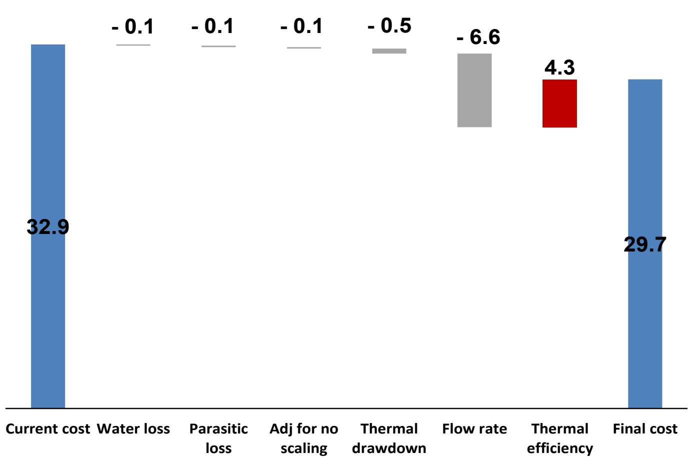


Figure 7. Impact of CO_2 as heat transmission fluid on LCOE, deep EGS scenario (2010 c/kW).

solubility of minerals in carbon dioxide than water. Due to lower specific heat capacity of carbon dioxide, thermal drawdown was reduced. Increased flow rates showed the highest impact on the LCOE. Adjustments were also done for lower thermal efficiency of carbon dioxide compared to water which showed a reverse trend increasing the cost of LCOE.

Our modeling efforts show a significant reduction in the LCOE for both deep and near-field EGS scenarios. This LCOE estimate is for an EGS plant only. We are currently working on estimating the total cost impacts of combining IGCC with CO_2-EGS.

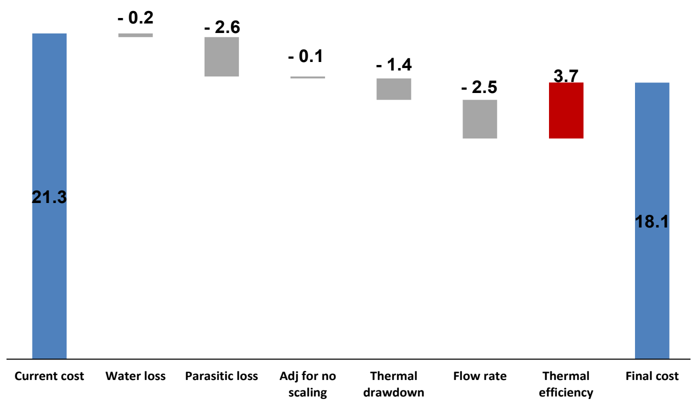


Figure 8. Impact of CO_2 as heat transmission fluid on LCOE, near-field EGS scenario (2010 c/kW).

Conclusions

We have explored the anticipated longevity of a prototypical sCO_2-EGS system coupled to an IGCC. In particular for the sCO_2-EGS system:

- sCO_2, fluid circulation at 1000 kg/s within a 0.1 km^3 reservoir for reasonable fracture spacings (10m – 100m) gives significant thermal drawdowns within a few months to a few years. These rates are unacceptably rapid.
- Where circulation rate is reduced to 100 kg/s then for all fracture spacings (<100m) the thermal drawdown is extended and 50% drawdown only occurs after about 20-50 years.
- Projected thermal declines at circulation fluid rates of the order of 100 kg/s are congruent with scaled drawdowns observed at prior demonstration projects (Fenton Hill and Rosemanowes).
- Circulation rates limited to the order of 100 kg/s per injection-withdrawal doublet requires that multiple doublets are assembled in some appropriate pattern, including five-spot or vertically or horizontally integrated arrangements.
- For reservoirs with a temperature of ~200°C and with 10% leak-off then the thermal output of the reservoir is about 50% of the electrical output of the electrical plant (Table 2). This thermal output scales in proportion to the reservoir temperature (400C gives W_{th}~W_e) and in inverse proportion to the leakoff rate (5% also gives W_{th}~W_e).

- Finally, preliminary cost estimates using GETEM for a CO_2-EGS plant alone show promising reductions in LCOE, which we are investigating further.

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Disclaimer

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