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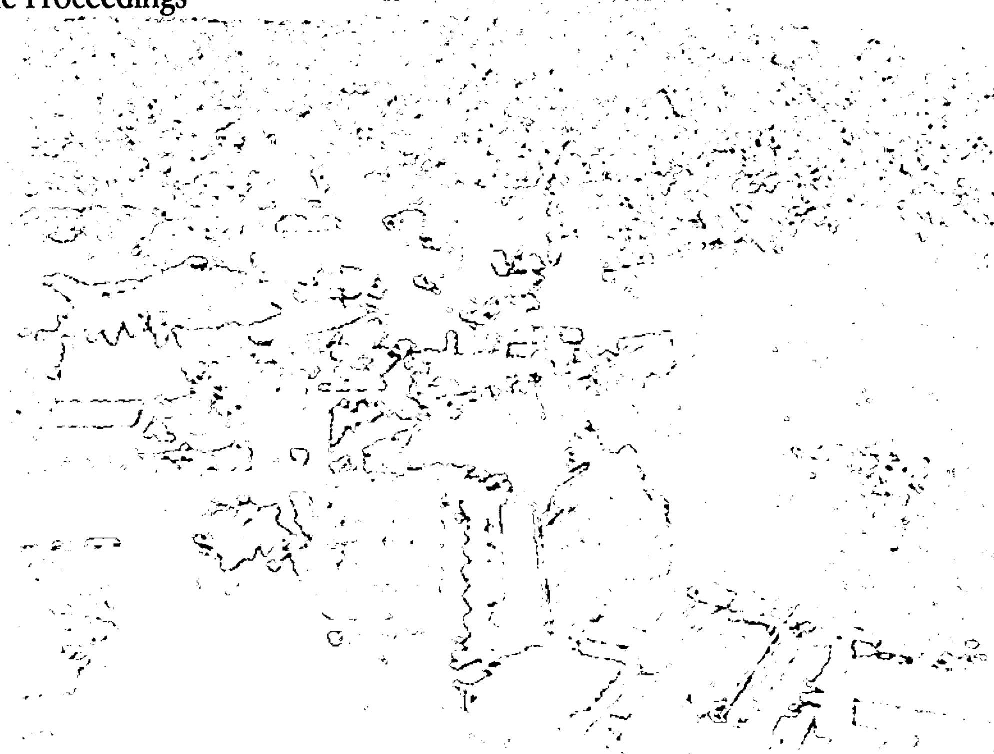

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COMPARISON OF THREE OPTIONS FOR GEOLOGIC SEQUESTRATION OF CO_2 - A CASE STUDY FOR CALIFORNIA -

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ABSTRACT

Options for sequestration of CO_2 are best viewed in light of the regional distribution of CO_2 sources and potential sequestration sites. This study examines the distribution of carbon emissions from fossil fuel power plants in California and their proximity to three types of reservoirs that may be suitable for sequestration: (1) active or depleted oil fields, (2) active or depleted gas fields, and (3) brine formations. This paper also presents a preliminary assessment of the feasibility of sequestering CO_2 generated from large fossil-fuel fired power plants in California and discusses the comparative advantages of three different types of reservoirs for this purpose. Based on a volumetric analysis of sequestration capacity and current CO_2 emission rates from oil/gas fired power plants, this analysis suggests that oil reservoirs, gas fields and brine formations can all contribute significantly to sequestration in California. Together they could offer the opportunity to meet both short and long term needs. In the near term, oil and gas reservoirs are the most promising because the trapping structures have already stood the test of time and opportunities for offsetting the cost of sequestration with revenues from enhanced oil and gas production. In the long term, if the trapping mechanisms are adequately understood and deemed adequate, brine formations may provide an even larger capacity for geologic sequestration over much of California.

INTRODUCTION

The State of California, has a population of 34 million people and supports an annual economy of $1,280 Billion per year, placing it amongst the top 10 economies in the world. Covering over 411,469 km^2, California encompasses a diversity of geologic terrains, from the volcanoes of the Cascade Mountain range in the north to the deep sedimentary troughs in the Central and Imperial Valleys in the south, from the Sierra Nevada Mountain range to the east and the 1500 km coastline to the west (see Figure 1). Rich in natural resources, it has the fourth largest oil and gas production in the United States, and extensive groundwater and surface water resources. All of these features make the State of California attractive for a regional case study for assessing the feasibility of geologic sequestration of CO_2.

Current annual CO_2 emissions from fossil fuel combustion in California total 380 million metric tons (MMT); of which 56.5% are from transportation, 16.2% from electrical generation, 14.4% from industrial sources such as refineries and cement kilns, 8.5% from residential heating and cooking, and 4.4% from commercial uses (California Energy Commission, 1998). Emissions are expected to increase about 10% by 2010 (California Energy Commission, 1998). Over 95%

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of the emissions from electrical generation come from oil/gas fired power plants, which provide over 55% of the electricity generating capacity in California. Coal-fired plants provide less than 1% of the installed generating capacity in California.

Large point sources are the most likely opportunities for geologic sequestration. Thus, this study focuses on assessing the feasibility of sequestering the 62 MMT of CO_2 emissions (16.24% of the total emissions) generated annually from oil/gas fired power plants in California (California Energy Commission, 1998). Three criteria were considered in this assessment, including (1) availability of potential sequestration sites within 150 km of the power plant, (2) capacity available for sequestration and (3) opportunities for offsetting the cost of sequestration with revenues from enhanced oil and gas production.

Figure 1: Map highlighting the major geographic features of California.

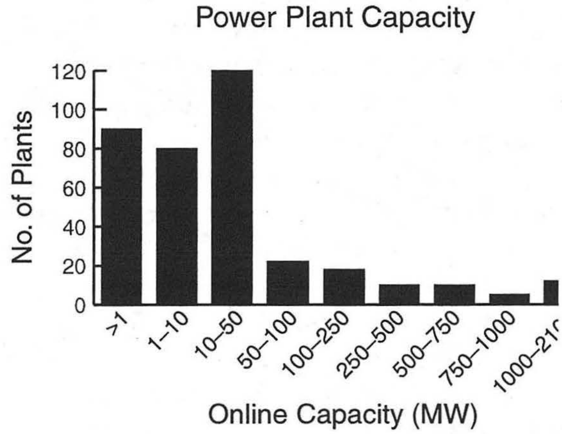

Figure 2: Distribution of the generating capacity of fossil fuel fired power plants in California

POWER PLANT PROXIMITY TO SUITABLE GEOLOGIC FORMATIONS

A total installed capacity of 28,850 MW is available from 355 fossil fuel fired power plants. Figure 2, a histogram showing the distribution of power plants by generating capacity, shows that the majority of these power plants generate less than 50 MW each. Although numerous, plants generating less than 50 MW only account for 18% of the total on-line capacity. The remaining 82% of the generating capacity is provided by the 61 plants rated for 50 MW or higher. Due to high infrastructure costs and the economy-of-scale gained from operating larger facilities, geologic sequestration is likely to be more cost-effective for larger facilities. As shown in Figure 3, the majority of the larger power plants are located near the major populations centers of the greater San Francisco Bay Area, the Los Angeles Basin and San Diego.

Figure 3 also shows the location of California's oil and gas fields, as well as the location of sedimentary basins that may contain brine formations suitable for sequestration. Comparison between the location of the power plants and the location of the oil and gas reservoirs and sedimentary basins illustrates that potentially suitable sequestration sites are located within 150 km of each of the power plants and that in many cases, potentially suitable sites are even closer. Power plants located in the greater San Francisco Bay Area are near the gas fields of the northern portion of the Central Valley. Power plants in the Los Angeles Basin and the southern part of the Central Valley (San Joaquin Valley) are located near extensive oil and gas reservoirs. Brine formations in the Central and Imperial Valleys are also potential sites for sequestering CO_2 emissions throughout the State.

SEQUESTRATION CAPACITY

Various approaches have been used to estimate the sequestration capacity of geologic formations. In depleted oil and gas formations, the most common approach has been to assume that the volume of oil or gas produced from the reservoir is replaced by CO_2 at the original reservoir pressure (Winter and Bergman, 1993; Hendriks and Blok, 1995). Alternatively, for active fields, estimates have been made by assuming the annual sequestration capacity is equal to the amount of oil or gas produced (Burruss, personal communication; Reichle et al., 1999). In some cases, the potentially important role that water will play in these estimates has been neglected. For example, sequestration capacity could be overestimated depending on the rate of natural recharge by water from surrounding formations. Alternatively, sequestration capacity could be underestimated because the large volumes of water often produced along with oil or gas may also be replaced by CO_2. In California, 7 barrels of water are produced for every barrel of oil, potentially increasing the sequestration capacity 7-fold. Other important, but perhaps second order factors, include dissolution of CO_2 in brine and oil, and formation of stable mineral phases.

Sequestration estimates for brine formations are even more challenging because far less information is available about them. Based on numerical simulation of CO_2 injection into a variety of generic brine formations, van der Meer (1995) concluded that, for practical purposes, from 1 to 6% of the reservoir volume is available for sequestration.

Preliminary estimates of the sequestration capacity in California have been made for oil, gas and brine formations using the methods described here. Additional work is needed to refine these estimates by including site-specific reservoir data, a better assessment of the role of water production on sequestration capacity and a better representation of geochemical interactions between CO_2 and the host formation. Nevertheless, these calculations provide a first-cut estimate of sequestration capacity and can serve as a guide to future investigations.

OIL RESERVOIR

Winter and Bergman, 1993, concluded that California was one of five states where depleted oil and gas reservoirs have significant capacity for sequestering CO_2. Commercial oil production in California began in 1876 and since that time over 28.1 billion bbl of oil (4.1×10^9 m^3) and 10^{12} m^3 of associated gas (at standard conditions) have been produced (California Department of Conservation, 2000). Currently, 311 million bbl of oil are produced annually, with 82% of this from on-shore wells. Annual gas production associated with oil fields is 284 billion cubic feet. Oil is produced in 16 counties from approximately 46,000 wells in 211 active oil fields (California Department of Conservation, 1997). Six giant fields, the Wilmington, Midway-Sunset, Kern River, Elk Hills, Belridge South and Huntington Beach, have each produced more than 1,000 million bbl. Fifty-two giant oilfields are expected to produce at least 100 million bbl each. Statewide production peaked in 1985 and has been declining slowly since then. A growing percentage of production comes from off-shore and, currently about 20% of all oil is produced from off-shore wells. Total reserves of recoverable oil in California are currently estimated at 3 billion barrels.

Most of the oil reservoirs in California are relatively shallow, with the majority of production coming from less than 1000 m. The shallow depth of these fields precludes exceeding the minimum miscibility pressure (MPP) for CO_2 and oil. Consequently, no commercial CO_2 floods are currently taking place in California. Seventy percent of the oil produced is classified as heavy oil, with an API gravity of 20° or below. Sixty-six percent of the oil is produced with enhanced recovery techniques, primarily thermal methods. A pilot project for CO_2 enhanced oil recovery will begin this summer in the Lost Hills Oil Reservoir, located in the southern part of the Central Valley.

The sequestration capacity has been evaluated based on two alternative approaches: (1) the cumulative volume of oil and gas produced is available for sequestration and (2) the annual volume of oil and gas produced could be replaced by sequestered CO_2. While important, the added capacity provided by produced water has been neglected because a significant fraction of the produced water is injected into the reservoir for waterflooding, steamflooding and pressure maintenance. Site specific investigations will be needed to evaluate the role of produced, injected and formation water on sequestration capacity. The sequestration depth is also a critical factor in evaluating sequestration capacity because the density of CO_2 is a strong function of pressure and temperature (Winter and Bergman, 1993). As mentioned above, the majority of oilfield production is from depths less than 1000 m in California. For this assessment, calculations were using three different assumptions about the average production depth: 300 m, 500 m and 1000 m. Assuming hydrostatic pressures and a normal geothermal gradient, the densities of CO_2 for these three average reservoir depths are 63 kg/m^3, 120 kg/m^3 and 496 kg/m^3.

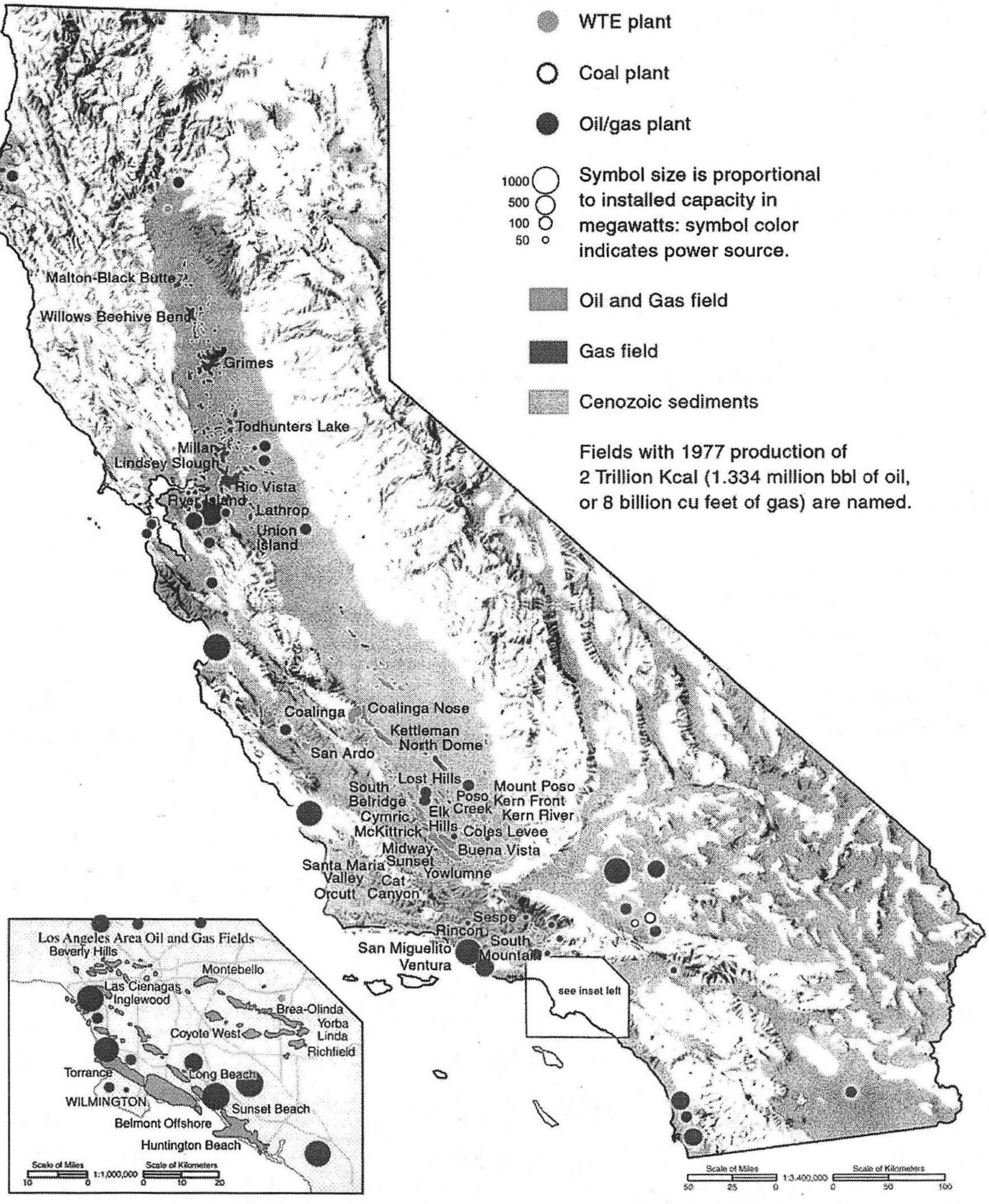

Figure 3: Map showing the location of power plants with greater than 50 MW online capacity and their proximity to geologic formations that may be suitable for sequestration.

Estimates of sequestration capacity based on cumulative production of oil and gas from oil fields in California range from 5 to 40 years of the current CO_2 emissions from power generation, depending on assumptions about the average reservoir depth. Alternatively, based on annual production rates, the capacity ranges from 30% to 100% of annual emissions. Associated gas production accounts for 20 to 60% of the annual sequestration capacity. Reservoir size is

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another important factor in assessing sequestration capacity. If the sequestration capacity of a particular reservoir is not large enough, creating the injection and monitoring infrastructure is unlikely to be cost effective unless revenues from enhanced oil recovery are large enough to be of commercial interest. Analysis of the cumulative and annual production from the six giant fields with cumulative oil production greater than 1,000 million bbl of suggests that these may each have the capacity to sequester emissions from a 1,000 MW power plant for many decades.

These analyses have not considered how sequestration capacity estimates would be affected by CO_2 enhanced oil recovery. While shallow depth of many oil fields precludes using a conventional CO_2 flood, the swelling and viscosity reduction achieved even with an immiscible flood may significantly increase oil recovery. In this case, sequestration capacity could be increased and the overall sequestration costs lowered by the offsetting revenues from enhanced oil recovery. Additional evaluation of the potential for combining and co-optimizing CO_2 sequestration with enhanced oil recovery is needed, especially for shallow reservoirs such as those in California.

GAS RESERVOIRS

California's Central Valley has 87 dry gas fields (not associated with oil production) and gas production has been underway since the early 1900s. The vast majority of these fields are located in the northern part of the Central Valley (also called the Sacramento Valley). Approximately 1,100 wells are currently producing gas from these fields. Cumulative production from the ten largest producers totals 5.7 trillion cubic feet, with a current annual production of 45 billion cubic feet (California Department of Conservation, 1997; 2000). Annual production from these ten fields is comparable to production from the remaining dry gas fields in the state.

Like California's oil fields, dry gas fields in California are relatively shallow, with most production coming from depths of less than 1500 m (California Division of Mines and Geology, 1962). For this assessment, calculations were made using three different assumptions about the average production depth: 500 m, 1000 m and 1500 m. Assuming hydrostatic pressures and a normal geothermal gradient, the densities of CO_2 for these three average reservoir depths are 120 kg/m^3, 496 kg/m^3 and 631 kg/m^3. As before, sequestration capacity has been evaluated based on two alternative approaches (1) the cumulative volume of gas produced is available for sequestration and (2) the annual volume of gas produced could be replaced by sequestered CO_2.

Estimates of sequestration capacity based on cumulative production from the ten largest gas fields in California range from 6 to 11 years of current CO_2 emissions from power generation, depending on assumptions about the average reservoir depth. Alternatively, based on annual production rates, the sequestration capacity ranges from 5% to 10% of annual emissions. These estimates may increase somewhat if all of the gas reservoirs are considered, however, sequestration in smaller fields may not be cost effective. The largest of the dry gas fields, Rio Vista Gas Field, has produced 3.5 trillion cubic feet of gas. Oldenburg et al (2000) conducted numerical simulations and concluded that CO_2 enhanced gas recovery may be feasible here and that up to 80 years of sequestration capacity for emissions from a nearby 680 MW power plant is available.

BRINE FORMATIONS

California's Central and Imperial Valleys are thick sedimentary basins with potentially significant sequestration capacity. The Central Valley, running nearly the full length of California is over 600 km long and up to 80 km wide. It is composed of marine, deltaic, lacustrine and fluvial sediments with a thickness ranging up to 8000 m. The lithology consists of siltstone, claystone and grained sandstone, but is dominated by the finer textured sediments. Marine layers tend to be continuous over extensive areas. The Imperial Valley, located in Southern California, is a broad sediment-filled valley filled with up to 6000 m of marine, lacustrine and deltaic sediments (Division of Mines, 1954). The Imperial Valley trends NW over 200 km and is from 30 to 100 km wide. Significant geothermal reservoirs are located along major faults within the valley and currently have installed capacity to produce up to 500 MW of electricity from four different reservoirs.

A large amount of information about both valleys is available from oil, gas and geothermal exploration. However, for the purpose of this preliminary assessment, site specific information is not used. Instead, it is assumed that somewhere in the depth interval between 1000 and 3000 m there is at least a 40 m thick formation (or set of closely spaced formations) that would be suitable for sequestration. This is a reasonable assumption based on geological considerations as well as extensive drilling data. It is also assumed that the average density of CO_2 will be about 560 kg/m^3 at this depth interval and that only 2% of the storage capacity will be occupied by CO_2. Using these assumptions, the estimated sequestration capacity of the Central Valley exceeds 300 years of the current state-wide annual CO_2 emissions from fossil-fuel fired power plants and 60 years for the Imperial Valley.

These calculations suggest that the sequestration capacity of brine formations in California may be large. However, California is located in a tectonically active area, with many major and minor faults intersecting these formations. The effect of these faults on sequestration capacity must to be evaluated, with respect to both trapping efficiency, as well as, the potential for induced seismicity and leakage associated with seismic events.

CONCLUSIONS

Based on a volumetric analysis of sequestration capacity and current CO_2 emission rates from oil/gas fired power plants, this analysis suggests that oil reservoirs, gas fields and brine formations can all contribute significantly to sequestration in California. Together they could offer the opportunity to meet both short and long-term sequestration needs. In the near term, oil and gas reservoirs are the most promising because the trapping structures have already stood the test of time and opportunities for offsetting the cost of sequestration with revenues from enhanced oil and gas production. In the long term, if the trapping mechanisms are adequately understood and deemed adequate, brine formations may provide an even larger capacity for geologic sequestration over much of California.

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