

generate 180kW. The unit was put into operation September 2008 and another unit designed to generate 250kW for three years was planned for delivery in early 2011 (Reinhardt et al. 2011). Another coproducing facility has very recently been installed in Huabei Oil Field near Beijing, China that is producing 300kW (Gong et al. 2011).

Other areas have shown great potential for coproduction application, particularly in the Gulf States (Sanyal and Butler, 2010). Erdalic et al. (2007) reported that Texas alone has thousands of oil and gas wells that are sufficiently deep to reach temperatures exceeding 250°F (121°C). The 2006 MIT report on the future of geothermal energy estimated that between California, Oklahoma, and six other states along the Gulf Coast over 11,000 MW could be generated from coproduced fluids which would double the world's current geothermal capacity. A more conservative estimate predicts at least 2,000 MW from these states.

While Gulf Coast states receive much attention for potential coproduction application California is another promising area for development, particularly in the Los Angeles (LA) basin. The LA basin is home to many giant oilfields and has been under production since the early 1900s. Production in the LA basin in 2010 was 97% water. Also, the LA basin has a promising geothermal gradient of 36°C/km and over 30% of its reservoirs reach to at least 1,800 meters which corresponds to at least 80°C. The LA basin has had a long history of water flooding but also a substantial amount of steam flooding; Wilmington, Huntington, Richfield, Inglewood, and Newport West oilfields have used steam floods, to name a few. After depleting these steam-flooded reservoirs of oil, some of the injected heat can potentially be recovered (Limpasurat et al, 2010). Another factor that makes the LA basin so attractive is the proximity to urban centers. Most of the oilfields in the region are intermingled with the city and thus have immediate access to the electrical grid. Figure 1 shows the oil fields of the Los Angeles Basin.

Wilmington Oilfield is a particularly attractive candidate for utilizing coproduction. Wilmington is the second largest oilfield in the state of California, has been under production since 1932 and has a 97% water cut. The deepest wells in the field reach over 2,500 meters where temperatures exceed 143°C. Operations are primarily conducted from four man-made islands just off the coast of Long Beach where space constraints mandate the use of electric submersible pumps instead of jack-arms for pumping; this represents a huge electricity demand that potentially could be met on site.

A process for screening potential candidates for coproduction is demonstrated here, using the Los Angeles basin as a case study. Temperature and production data were incorporated into a simple STARS numerical model to forecast reservoir performance over the course of 30 years and power output from a binary power plant. These results were then used in an economic model to determine the net present value of the project. The most significant parameters to economic viability for a project include reservoir temperature as well as total fluid production rate.

ANALYSIS

Temperature and Production Data

Temperature and production data from oilfields in the Los Angeles basin were acquired from the State of California, Division of Oil, Gas and Geothermal Resources (DOGGR) databases. Out of the 365 producing reservoirs in the Los Angeles basin, 189 had initial temperature data. Figure 2 shows the temperature versus depth for these reservoirs identifying the oilfields from which the four hottest individual reservoirs are found. A geothermal gradient of approximately 33°C/km is determined which resembles the 2.0°F/100ft (36.5°C/km) geothermal gradient found by Sanyal et al. 1993. The data scatter is in part caused by inaccuracies inherent in the database. One reason for this inaccuracy is that temperatures are usually recorded in wells during logging runs where the temperature may or may not have recovered from the cooling effect of mud circulation, thus temperature records often underestimate the actual reservoir temperature (Sanyal et al. 1993).

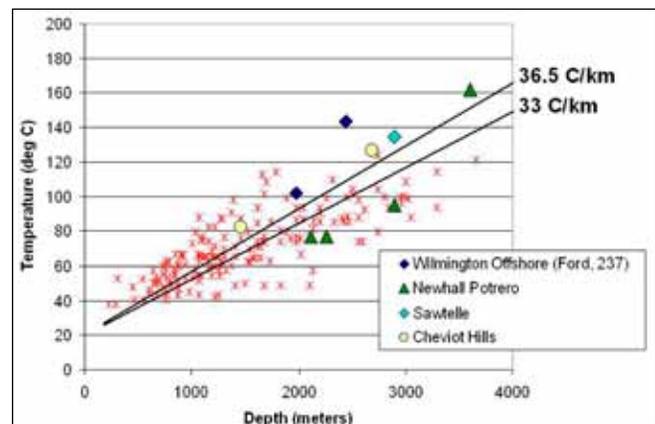


Figure 2. Depth vs reservoir temperature for oil reservoirs in the Los Angeles basin.

Of the 189 reservoirs with initial temperature data, 11% recorded temperatures exceeding 100°C and 32% recorded temperatures above 80°C. Reservoirs with depths exceeding 2,500 meters account for 12% of all the reservoirs which, by following the geothermal gradient, can indicate temperatures exceeding 100°C. Reservoirs with depths exceeding 1,800 meters account for 33% of all reservoirs which, again by following the geothermal gradient, can indicate temperatures exceeding 80°C. Overall, the Los Angeles basin contains a significant number of reservoirs with temperatures within the limits of binary technology to be exploitable through coproduction.

Production and injection rates for March 2011 for each field and reservoir were acquired from the DOGGR databases. Production and temperature data for promising fields are listed in Table 1. Notice that while certain zones of the Wilmington Offshore oilfield show very promising temperatures, the overall average temperature of the whole field is below the limits of being useful for electricity generation. This is because the most prolific zone by far in the Wilmington field, Ranger, happens to be shallower and

cooler (61°C). Unfortunately, as geofluids from various zones in the Wilmington field are comingled during production, additional infrastructure may be required to keep the geofluids of different temperatures separate before installing a binary power plant. For this analysis, zones Tar and Ranger in Wilmington field are left out leaving reservoirs Upper Terminal, Lower Terminal, Union Pacific, Ford, and 237.

Table 1. Selected production data for fields of interest

Field	Average Reservoir Temperature (°C)	March 2011 Combined Production (kg/s)	water cut
Beverly Hills	97	49	92%
Long Beach	79	230	97%
Inglewood	68	674	97%
Santa Fe Springs	73	183	98%
Seal Beach	100	43	95%
Wilmington (All)	63	2514	98%
Wilmington (UT, LT, UP, Ford, 237)	77	856	97%

STARS Numerical Model

A numerical model programmed in STARS was used to forecast reservoir performance over the next three decades specifically calculating reservoir temperature decline as a result of mining the heat to produce electricity instead of reinjecting that thermal energy. (Three decades was selected as the typical lifetime of a binary power plant). The model is a basic two well model, simulating a single injector and producer pair in a closed system. The model assumes no aquifer, no heat source or sink, and two fluid phases (water and oil). Reservoir size, temperature, production and injection rates were customized for each simulation while geologic properties including porosity, permeability, viscosity, relative permeability, thermal conductivity, etc. were borrowed from an actual typical sandstone reservoir and used for all simulations. A list of some of the parameters is included in Table 2.

Table 2. Constant parameters for the STARS numerical model

Ambient Temperature	24°C
Injection Temperature	35°C
Power Plant Outlet Temperature	55°C
Porosity	0.30

The STARS model was used to simulate a single injector and producer pair and the results were then properly scaled to represent the entire field. Separation of the oil and water was assumed to occur after running the coproduced fluid through a heat exchanger at the binary power plant. The production rates are significantly lower in these oil wells than what is typically desired for geothermal applications and significant

thermal breakthrough within 30 years was not observed for any of the simulations. Later in the economic analysis, it became apparent that sufficient fluid flow is just as or even more important that sufficient thermal energy.

Power Output Analysis

The 2006 MIT report exhibits a correlation for specific power output of a binary power plant considering the inlet (produced) temperature and the outlet (injected) temperature. This correlation is only provided for select inlet and outlet temperatures shown in Figure 3.

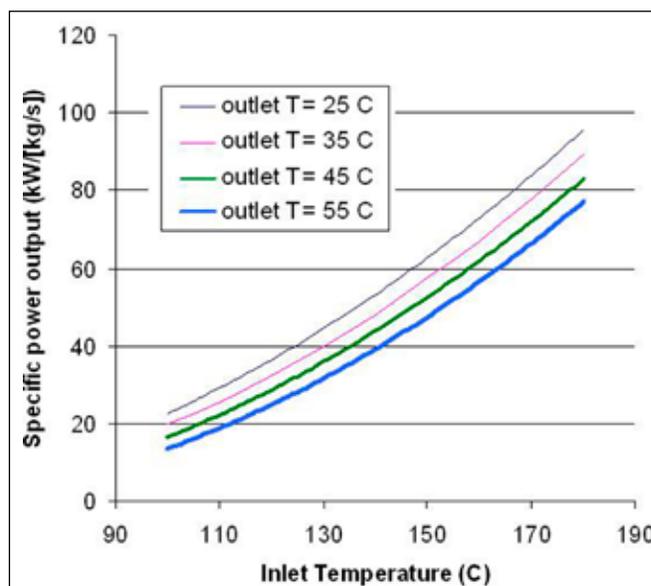


Figure 3. Specific power output in kW/[kg/s] for low to moderate temperature geofluids as a function of inlet temperature (produced temperature) and outlet temperature (injected temperature) from 2006 MIT Report.

A more complete correlation was fit to be able to account for any specified inlet and outlet temperature:

$$\text{Specific Power} = 0.0037(T_{inlet} - X)^2 - 0.1217(T_{inlet} - X) - 2.0381$$

$$\text{Where } X = 0.5638T_{outlet} - 14.507$$

Economic Analysis

Basic economic assumptions are listed in Table 3. The electricity generated by coproduction is assumed to be used on site to offset the electricity purchased from the grid at \$0.08/kWh instead of being sold to the grid at the lower wholesale price (EIA, 2011). The initial capital cost of the power plant and gathering system includes the cost of the additional pipelines, pumps, on site substation and transmission lines, pollution abatement, legal, regulatory, reporting and documentation, as well as the power plant itself which comes to around \$1,900/kW installed capacity (GeothermEx, Inc, 2004). There are no exploration or development costs involved since the oilfield infrastructure is already in place. No tax rebates are included in hopes of viability without tax credit intervention. On a similar note, taxes and specifics of project financing are not addressed in

this analysis. Other relevant parameters not explicitly mentioned are also listed in Table 3. A project is considered economic only if it has a net present value (NPV) exceeding \$1M at the end of 30 years, a typical lifetime for such a power plant.

Table 3. Basic economic parameters

Electricity Price	\$0.08/kWh
Initial Capital Cost	\$1,900/kW
Operation and Maintenance	\$0.014/kWh
Power Plant Capacity Factor	0.85
Discount Rate	5%

RESULTS AND DISCUSSION

This analysis covers 49 active oil fields in the LA basin incorporating 365 individual reservoirs. All together, these fields have the potential to produce 8.2 MW for 30 years using a power plant outlet temperature of 55°C. (Potentially employing water cooled systems and thus a power plant outlet temperature of 35°C could boost production to 18.7 MW). Figure 4 shows the power potential from each of the 49 fields compared with the economic success criteria labeling only select fields. Only six fields have a sufficient temperature and flow rate in order to be economic independently: Beverly Hills, Long Beach, Santa Fe Springs, Seal Beach, Inglewood, and select reservoirs of Wilmington. Together these six fields total 7 MW. Table 4 shows the power plant size that can be sustained for 30 years by the forecasted production rates and temperatures of the fields as well as the net present value of each of the projects.

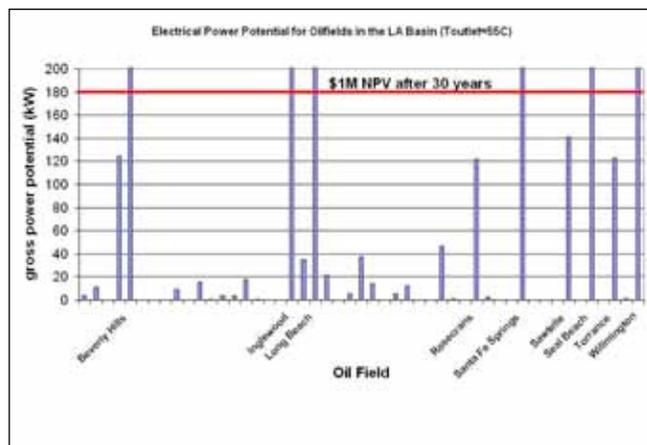


Figure 4. Gross power potential from each of the 49 active oilfield in the Los Angeles Basin with the economic success criterion of \$1M NPV after the 30 year life of the power plant. The gross power potential scale is terminated at 200 kW to detail the smaller fields.

The six fields that are economical end up being those with only moderate temperatures but prolific flow rates demonstrating that sufficient flow is just as, or even more, important than reservoir temperature. To demonstrate this consider Newhall Potrero oilfield which has the highest recorded temperature in the LA basin: 162°C in zone 7. Development of this zone alone results in a 9 kW power plant

sustained for 30 years but uneconomic. Although the temperature of the reservoir is sufficiently high, production rates are not, which seriously limits the potential power generation. Considering all zones in the Newhall Potrero field results in a 14 kW power plant sustained for 30 years which is still uneconomic. It is observed that even lower producing temperatures can be compensated for by higher production rates which explains why the largest fields, and not necessarily the hottest, are the most economic for coproduction.

Table 4. Power plant size that can be sustained for 30 years and the net present value.

Field	Power Output (kW)	NPV
Beverly Hills	1,080	\$3,283,431
Long Beach	530	\$5,995,589
Inglewood	580	\$6,095,423
Santa Fe Springs	1,100	\$2,945,104
Seal Beach	590	\$3,205,782
Wilmington (UT, LT, UP, Ford, 237)	3,550	\$19,650,668

The Wilmington Offshore oilfield represents a lower limit to this trend of trading extremely high temperatures for higher flow rates. Excluding the two shallowest and coolest zones, Ranger and Tar, the Wilmington oilfield can sustain a 3.55 MW power plant for 30 years which results in NPV of over \$19.6 million. In this case, the development scenario cannot be improved by incorporating more lower temperature zones to boost production. The most prolific zone in the Wilmington Offshore field, Ranger, accounts for 84% of the entire production and unfortunately has a reservoir temperature of only 61°C. The temperature of the produced fluid after comingling is only 63°C. Unfortunately this happens to be the case for production in Wilmington offshore at present – geofluids from multiple zones are comingled in the production process. New infrastructure might be necessary before utilizing Wilmington offshore for coproduction.

CONCLUSION

This paper presents a process for analyzing potential reservoirs for coproduction using oilfields in the Los Angeles basin as a case study. Potential developments are ranked according to the size of power plant it can sustain for a typical power plant life time of 30 years as well as the net present value of the project. Six fields are shown to have sufficient flow and reservoir temperature to be economic independently: Beverly Hills, Long Beach, Inglewood, Santa Fe Springs, Seal Beach, and select zones of Wilmington. Taking a closer look at the single hottest reservoir in the LA Basin, Newhall

Potrero's zone 7, demonstrates that sufficient production rate is as important to development as reservoir temperature.

This analysis is executed on a by field basis but perhaps a second analysis by operator is warranted since multiple operators developing from the same field would most likely be unwilling to comingle production for a binary power plant.

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