Economics of Steam Generation for Thermal Enhanced Oil Recovery

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Summary
The thermal-enhanced-oil-recovery (EOR) steam-generation projects in Persian Gulf oil fields are on such a large scale that they affect an entire country's economic position. As such, the policies related to oilfield steam generation should be decided at the national level by use of the cost of the marginal fuel. This paper calculates the steam cost for three methods: once-through steam generator, once-through heat-recovery steam generator, and solar steam generator. Detailed performance and economic models of the steam-generation methods were created and used to calculate the levelized cost of energy (LCOE) and the fuel break-even (FBE) price. The environmental and economic burdens on the cost of steam generation are explored. The effect of fuel price on the cost of steam is also analyzed, with a focus on the marginal fuel price. Finally, the limitation of cogeneration in an isolated oil field, where the energy demand necessitates electricity-matched cogeneration, was analyzed. This limitation, along with the steam cost at the marginal fuel price, provides the decision maker with a steam-supply curve.

For the case analyzed in this paper, the cost of solar steam is lower than that of cogeneration or a simple boiler for fuel prices greater than USD 5/million Btu.

Introduction
Of the remaining oil reserves in the world, only 30% are considered "conventional" or "light oil" (with °API of 22 or lighter), while the remaining 70% are heavy. According to the International Energy Agency, boosting oil recovery of these heavier crudes could unlock approximately 300 billion bbl of oil.

There are three main categories of EOR: thermal, miscible gas injection, and chemical. Thermal methods are mainly applicable to heavier crudes at shallower depths, and these thermal methods represent the majority of global EOR production, accounting for 2.3 million B/D in 2013 (Kokal and Al-Kaabi 2010).

Some of the largest thermal-EOR projects in the world are in Canada, Russia, Venezuela, Indonesia, California, Oman, and (soon to be) Kuwait. The steam generated for thermal EOR consumes 1.7 Tcf/yr of natural gas. Thermal-EOR projects tend to be very long-term projects by oilfield standards. In California, many of the oldest steamflood projects have been running for 40 or 50 years. The super-giant-heavy-oil fields of the Middle East may produce for a century or more. With natural gas becoming increasingly constrained and expensive in many parts of the world, there is a need to better understand the economics of steam generation.

Because this paper discusses the combination of traditional sources of generating steam with solar steam generation, the focus is on countries with sufficient sunshine and constrained natural-gas supply, such as Oman, Kuwait, Saudi Arabia, Bahrain, and Egypt. The EOR potential of these countries is estimated at 475 billion bbl of oil. The example used to analyze the economics is of a field in southern Oman. However, the methodology is applicable to any field.

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Steam Generation for Thermal EOR
Three methods of steam generation have been considered **(Fig. 1):**
- Fuel-fired once-through steam generator (Boiler)
- Cogeneration (Cogen) with a power plant by use of a once-through heat-recovery steam generator
- Solar steam generator (Solar) by use of concentrating solar power (CSP)

The first method, Boiler, burns fuel directly to generate steam. Boilers have the most-flexible operations, but are most dependent on fuel costs.

The second method uses the high-temperature flue gas from the gas turbine (GT) as "waste heat" to produce steam in a once-through heat-recovery steam generator (Cogen). Cogen steam production is linked to the power production of the GT. Operators sometimes add supplementary firing to the Cogen, called duct burners. The steam produced from duct burning has the advantage of rebalancing the electricity vs. thermal demand, but it is linked directly to fuel price.

The third method, Solar, uses mirrors to concentrate the sun's energy to generate steam. Three solar steam plants have been built: The 21Z in California (2011) and the Amal SSGP in Oman (2012) use enclosed-trough technology, and the Coalinga project in California (2011) uses tower technology. Coalinga ceased solar operations in 2014. In July 2015, a 6,000-tons-of-steam/D (1-GW) enclosed-trough solar plant (Miraah) was announced in Oman. Solar has the highest capital expenditure (Capex) of the methods considered, but consumes no fuel.

The pros and cons of these three methods are summarized in **Table 1.**

Middle East Fuel Pricing
The fuel price throughout the countries in the Gulf Cooperation Council (GCC) and the broader Middle East varies greatly, but the common theme is its subsidization. While the current cost of production in the Gulf nonassociated fields is approximately USD 5 to 8/million Btu (Dargin 2013), the price at which gas is sold to the end user is typically a fraction of that price, averaging just USD 1.50/million Btu (Dargin and Vladimirov 2012).

Dargin has written extensively on the topic of gas pricing in the region and has argued that price reform is an essential step to increasing availability of natural gas and improving energy efficiency in these countries.

Another factor facing these countries is the price of the marginal fuel. Countries such as Oman and Kuwait are gas-constrained, and the marginal fuel is either imported liquefied natural gas (LNG) (or lower LNG exports) or diesel and other liquid fuels.

For these reasons, we have chosen to run our economic analysis using two tiers of gas prices. The first is representative of true gas-production costs in the region for nonassociated-gas fields and is taken to be an average of USD 6/million Btu. The second is the expected long-term LNG market price (or opportunity cost), taken to be USD 13/million Btu.

Macroeconomic Considerations
There are two significant concerns of fuel-fired steam generation. The first is the broader nationwide implication of diverting natural gas from steam generation to economic development. An increase

Boiler

Cogen

Solar

Fig. 1—The three methods of steam generation.

in the amount of gas available for domestic use will allow for investments in industry and subsequent job creation. The second concern is the environmental impact of greenhouse-gas emissions. These two concerns are addressed in the Economic Burden and the Environmental Burden subsections.

Economics of Steam Generation

The first step in analyzing the cost of steam generated from the various methods is to calculate each on a standalone basis. The methods were compared using the real LCOE of the steam produced, as calculated by the solar adviser model:

$$LCOE_{\text{real}} = NPV(Total\ Cost\ Of\ Ownership)_{\text{nominal discount rate}} / NPV(Total\ Energy\ Produced)_{\text{real discount rate}}, \quad (1)$$

where NPV is the net present value.

The inputs to the numerator include cost data [Capex, operational expenditure (Opex), and fuel cost], as well as economic and environmental burdens. The input to the denominator is the steam produced, which is dependent on the performance of the method chosen. A fair comparison between the three methods of steam production can be achieved only if all methods are "fully burdened." The burdens considered are economic and environmental.

Economic Burden. The economic burden considered for the Cogen is the opportunity cost of the "waste heat" from the GT exhaust. The decision maker may assume that waste heat into the Cogen is free. This is not accurate. In reality, the Cogen is dependent on the price of natural gas by its direct connection to power generation. The waste heat has an economic value that is equal to the opportunity cost of producing more power and water in an optimized plant configuration.

Fig. 2 illustrates the energy flow for two different scenarios of fuel use. In one, a simple-cycle (SC) power plant (PP) is connected to the Cogen to produce steam. In the other, a combined-cycle (CC) PP produces more power for the same fuel consumption, and it can also produce water with no additional energy use.

The power-opportunity cost is calculated by comparing the economic value created with the more-efficient CCPP with the SC configuration by use of Cogen. This opportunity cost is a result of two factors: the LCOE of power generated by a CCPP ($LCOE_{CC}$) is lower than that of an SCPP ($LCOE_{SC}$), and for the same amount of fuel, the CCPP will produce more electricity than the SCPP, calculated by the inverse of the heat rate (1/HR). Thus, the formula for the power-opportunity cost is:

$$\text{Power-Opportunity Cost} = \{(LCOE_{SC} - LCOE_{CC}) \times (1/HR_{CC} - 1/HR_{SC})\} \times Fuel\ Consumed_{SC}. \quad (2)$$

The water-opportunity cost is calculated by comparing the cost of water (CW) produced by a combined water and PP that uses a thermal-desalination method, such as multieffect distillation (MED), with an independent water plant that uses an electrical-desalination method, such as reverse osmosis (RO). The assumption is that the MED plant will replace the condenser in the CCPP and is sized accordingly. We then compared the CW of the Cogen MED plant with a standalone RO plant, where its cost of electricity is $LCOE_{SC}$. The difference in the CW for the two configurations is then multiplied by the total potential water production in the combined water and PP configuration to calculate the water-opportunity cost for the fuel consumed. Thus, the formula for the water-opportunity cost (Fichtner 2011) is:

$$Water\text{-}Opportunity\ Cost = (CW_{RO} - CW_{MED}) \times (Water\ Produced\ in\ Combined\ Water\ and\ Power\ Configuration). \quad (3)$$

Another indirect benefit of displacing natural gas from steam generation is the direct and indirect jobs it creates. This has not

Method	Pros	Cons
Boiler	- Low capital cost per ton of steam produced - Short construction time - Flexible and controllable steam output	- Cost of steam is highly dependent on fuel price
Cogen	- Low capital cost per ton of steam produced - Increases system efficiency of simple-cycle power plant	- Linked directly to power generation - Indirectly consumes natural gas - Duct burning dependent on fuel price
Solar	- Does not consume fuel - Does not produce greenhouse-gas emissions - Can extend field life	- High capital cost - Dependent on weather

Table 1—Summary of the pros and cons of the three steam-generation methods.

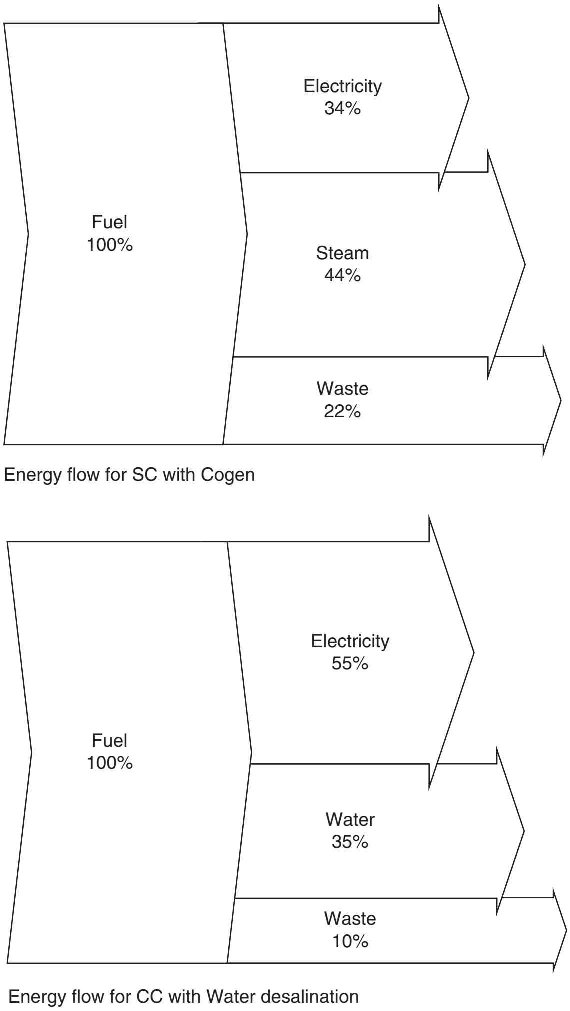

Fig. 2—Energy flow for different scenarios.

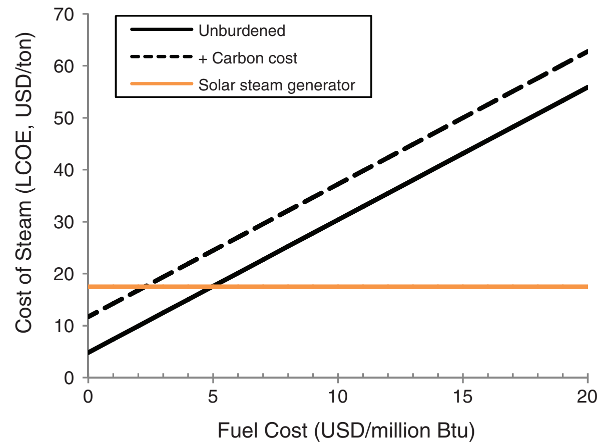

Fig. 3—LCOE of once-through steam-generator steam generation.

been considered here. No economic burdens have been applied to the Boiler.

Environmental Burden. The environmental burden considered is the carbon cost, and it is applied to the Boiler and Cogen methods. The emissions are calculated by use of the emission factors defined in *AP 42, Compilation of Air Pollutant Emission Factors* (EPA 2015). For Cogen, because fuel is burned (and carbon emitted) in the GT, it is necessary to allocate the emissions fairly between power and steam. The assumption is that, in the Cogen plant, the emissions allocated to electricity production are calculated by use of the emissions intensity of a more-efficient CCPP (tons CO_2/MW-hr). Therefore, the emissions allocated to steam production are the difference between the total emissions of the SCPP and the calculation mentioned in the preceding. Thus, the formula for the Cogen carbon cost is

$$\textit{Cogen Carbon Cost} = [\textit{Emissions}_{SC} - (\textit{Power}_{SC} \times \textit{Emissions Intensity}_{CC})] \times (\textit{Carbon Cost}/\text{ton}). \quad (4)$$

The carbon cost of the once-through steam generator is simply the emissions and carbon cost per ton. The carbon cost used is USD 40/ton of CO_2 and is based on the range of internal carbon prices used by the oil majors [Total: USD 34; Shell & BP: USD 40: Exxon Mobil: USD 60 (CDP North America 2013)].

Performance Models

The denominator of the LCOE calculation is the total energy produced by the various methods. To calculate the LCOE of the various steam-generation methods accurately, it was necessary to build performance models that take into account regional weather data.

For the Cogen method, we created a performance model for a typical GT and connected a once-through heat-recovery steam generator. The detailed performance-model methodology and calculations are shown in Appendix A.

The solar-performance model is built off GlassPoint's proprietary model and operating experience at the solar steam-generation plant in Amal, Oman.

LCOE Models. The LCOE models for the Boiler, Cogen, and Solar methods are built to provide a fair comparison of the methods. One factor affecting the LCOE is the size of the project. The assumption is that the Solar and Boiler are built to match the size of the Cogen, which, as discussed previously, produces 5,525 tons/D of steam on an annual average. Also, the same macroeconomic assumptions were used for all methods of steam generation, such as nominal discount rate (8%), inflation (3%), and project life (25 years).

Solar Model. To match the steam generated by the Cogen, 32 blocks of GlassPoint solar steam generators are required. The assumed availability is 99% on the basis of GlassPoint's experience at Amal SSGP. The Capex used is based on GlassPoint's estimate of a project this size and is in line with the recently announced Miraah project planned in Oman. The solar steam LCOE was calculated to be USD 17/ton of steam.

Boiler Model. The assumed boiler firing rate is 85 million Btu/hr, which corresponds to 800 tons/D of steam. To match the steam generated by the Cogen and to account for an availability of 90%, eight boilers are required. The once-through steam-generator efficiency is assumed to be 85%. The boiler-steam LCOE was calculated with and without the environmental burden of carbon cost, and the results are displayed in **Fig. 3.**

Cogen Model. The Cogen Capex was based on estimating software and a premium added for installation at an oil field (because of higher costs of health, safety, and environment and logistics).

The Cogen LCOE model is also affected by the PP models generated for the SC and CC configurations (power-opportunity cost). For the PPs, heat rates were taken from the EBSILON®Professional (by STEAG Energy Services) heat-balance models built for this study. Overnight capital costs were taken from various press releases on similar projects and from the *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants* report issued by the Energy Information Administration (EIA) (EIA 2013). Fixed and variable operations and maintenance costs were also taken

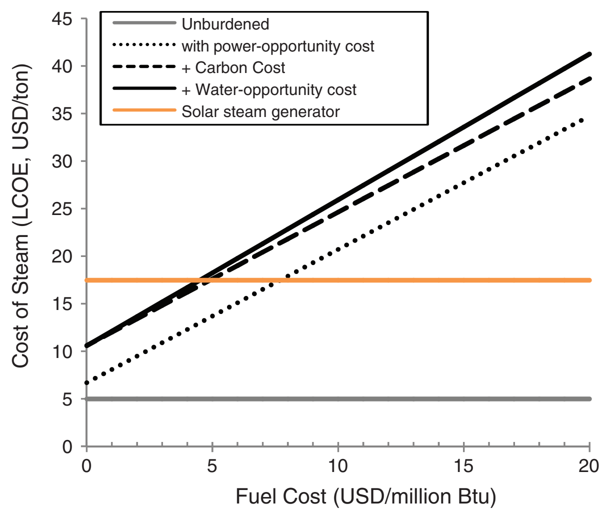

Fig. 4—Cogen steam-generation cost vs. fuel cost.

from the EIA report. Capex and Opex for the SC/Cogen plant were escalated to account for higher installation and operation costs at the oil field. Capacity factors were from our models or the EIA's *Annual Energy Outlook 2014* (EIA 2014). The PP LCOE calculated is the real LCOE calculated by use of the National Renewable Energy Laboratory (NREL) method.

This LCOE calculation neglects taxes, tax incentives, government subsidies, and Capex not directly related to the cost to procure and install the plant equipment. It represents the minimum price at which energy from the project must be sold in order for the project to cover its costs. It is a useful metric for fairly comparing one project with another.

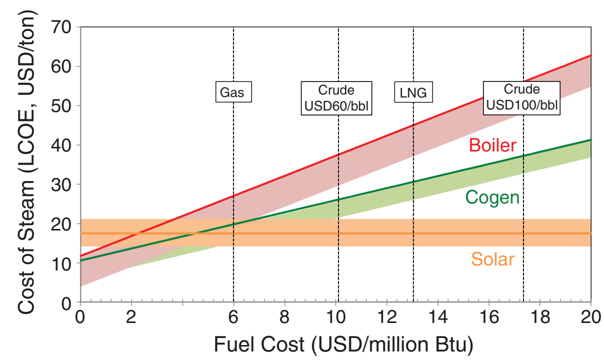

Fig. 5—LCOE vs. fuel cost.

Also, the Cogen LCOE is affected by the water model, described in the water-opportunity cost and whose input is taken from Fichtner (2011). The Cogen steam LCOE was calculated with and without the economic and environmental burdens across a range of fuel prices, as shown in **Fig. 4.**

Summary of LCOE Results. **Fig. 5** shows a summary of the fully burdened LCOEs for the three methods of steam generation and their relationship to the fuel price.

As discussed in the following, the cost of Solar is not fixed and depends on externalities. In Fig. 5, the range of costs for Solar is shown in the band. Also, the range of Cogen and Boiler steam costs, as discussed previously, are shown in bands.

What is clear in Fig. 5 is that the question of which method of steam generation is best is answered only by another question, "what is the fuel cost?" These questions should be considered at the countrywide level by use of the marginal fuel. As mentioned previously, many countries in the Gulf region have multitiered and subsidized fuel costs, which do not reflect the true economic value. If a country is subsidizing gas to approximately USD 1.50/million Btu and is also importing liquid fuels at USD 13/million Btu, then the fuel price that should be used in decision making should be the marginal cost, which could be LNG, diesel, or even crude. From **Fig. 6,** we can see that the fully burdened costs of steam from a once-through steam generator and Cogen at gas prices more than USD 6/million Btu are higher than the cost of steam from Solar. Also, Solar is independent of fuel price and is USD 17/ton of steam regardless of the alternative fuel price.

The LCOEs for all scenarios are shown in **Table 2.**

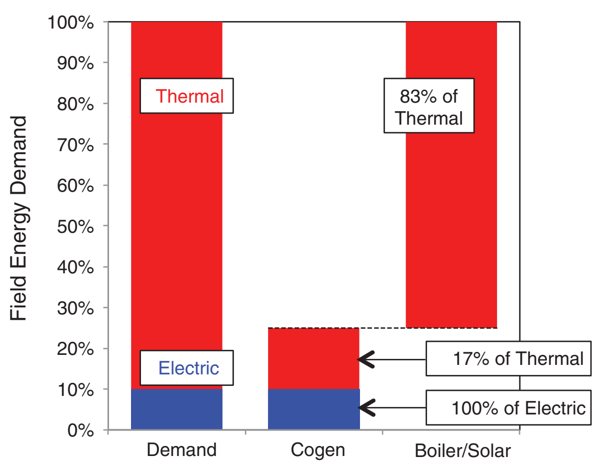

Fig. 6—Electricity-matched Cogen system.

FBE Models. A useful economic indicator that allows a decision maker to compare the fully burdened cost of steam from the mentioned methods is the FBE price. This fuel price results when the total cost of ownership from the fuel-fired steam-generation method (either Boiler or Cogen) is equal to that of the Solar. The FBE price allows a decision maker to compare the economics of the

Scenario		LCOE (USD/ton) Solar	Boiler	Cogen
Fuel Price: USD 6/million Btu	Unburdened	17	20	5
	With power-opportunity cost			15
	Plus carbon cost		27	19
	Plus water-opportunity cost			20
Fuel Price: USD 13/million Btu	Unburdened	17	38	5
	With power-opportunity cost			25
	Plus carbon cost		45	29
	Plus water-opportunity cost			31

Table 2—LCOE for all scenarios.

Scenario	FBE (USD/million Btu) Solar vs. Boiler	Solar vs. Cogen
Unburdened	4.95	
With power-opportunity cost		7.70
Plus carbon cost	2.25	4.90
Plus water-opportunity cost		4.50

Table 3—Fuel break-even (FBE) price for various burden scenarios.

various methods of steam generation on the basis of the marginal cost of fuel.

The FBE price for Solar when compared with a fully burdened Boiler is only USD 2.25/million Btu, and the FBE price for solar when compared with a fully burdened Cogen is USD 4.5/ million Btu. The FBE price for various burden scenarios is shown in **Table 3.** Note that, as discussed previously, the unburdened Cogen has no dependence on fuel price, therefore it is not possible to calculate its FBE price. Similarly, the Boiler does not have power- or water-opportunity costs, so they were not calculated.

Steam/Oil-Ratio (SOR) Calculation. Another helpful indicator is the break-even SOR, where the cost of steam injected is equal to the value of the oil produced. **Table 4** shows the marginal SOR at USD 60/bbl of oil price.

Factors Affecting the Economics of Steam Generation. The economic calculations in the preceding are all based on the specified assumptions. However, the economics of steam generation is dependent on various inputs, and sensitivities should be calculated to refine the output. Some of these factors are included in **Table 5.**

Oilfield Energy Requirements

Once the economics of the various methods of steam generation are calculated, it is necessary to determine the mix of the various methods of steam generation. To do so, the decision maker needs to understand the energy requirements and limitations at the oil field. Welch (2011) summarized the decision-making process for steam-generation methods as follows:

> "…a gas turbine cannot exactly match the electrical load required and provide all the heat required. This gives the Operator a choice of whether to install a heat-matched system or an electricity-matched system. In a heat-matched system, the Gas Turbine is selected on the basis of its ability to provide all the heat required, which means that it is likely to generate far more electrical power than the production facilities themselves require. This necessitates the export of surplus electrical power to the local power network. In an electricity-matched system, the Gas Turbine is selected to provide just the power required by the production facilities, while the shortfall in steam is made up by installing additional conventional fired boilers."

Macroeconomic Planning

The analysis of the economics of steam generation has to be considered in the broader macroeconomic policy and planning of a government or its national oil company. The first step is to understand the decision maker's marginal fuel cost, which will specify the preferable method of steam generation. The next step is to understand the limitations to producing steam from the Cogen. By definition, steam from cogeneration is linked to electricity production, which is constrained by the oilfield power demand or the ability to export power to the grid. It is necessary for the decision maker to analyze the combination of steam-generation methods through two different lenses—isolated oil field or connected oil field.

Boiler	Cogen	Solar
Marginal fuel price		Solar radiation
Carbon price		Project size
Labor costs		

Table 5—Factors affecting the economics of steam generation.

SOR Break Even	Oil Price: USD 60/bbl
Solar	22
Boiler	14
Cogen	19

Table 4—Marginal SOR at USD 60/bbl of oil price.

Isolated Oil Field. In this scenario, the ability to generate steam with cogeneration is limited by the total power requirement in the oil field. This necessitates an electricity-matched system.

The isolated oil field's energy split between thermal and electrical demand is highly dependent on the type of field (quantity of heavy oil vs. lighter crude) and its boundary (number of reservoirs that are operated within the field boundary). For a standalone heavy-oil field, upstream electricity demand may be only 2% of total energy demand during a steamflood. In an electricity-matched system, the PP is sized to deliver the power required by the field. The electrical-/thermal-energy split delivered by a Cogen plant is approximately 1:1.5. To illustrate the limitations of the isolated oil field, it is assumed that 10% of the field's energy requirements are electric. **Fig. 6** illustrates this scenario, in which the Cogen plant is electricity-matched (delivers all electric-energy demand) and delivers an additional 15% of total energy demand as thermal energy. Thus, the Cogen delivers 17% of thermal-energy demand. The remaining 83% of thermal demand must be satisfied with another method of steam generation, either Boiler or Solar.

Connected Oil Field. In this scenario, it is assumed that the entire country (or region) is connected to the same power grid as the oil field. The oil field can use a heat-matched system and export the surplus power to the grid.

Brandt and Unnasch (2010) have studied the energy requirements at various California thermal-EOR fields and found that the average operator generates only 40% of its steam from cogeneration. The implementation of large-scale cogeneration for thermal EOR in a grid-connected oil field has macroeconomic implications that should be studied further and should be considered the topic of another paper.

Hybrid-Steam Generation

Steam produced by Solar is inherently dependent on solar radiation and will produce variable output. Two SPE papers, van Heel et al. (2010) and Sandler et al. (2012), studied the effect of injection-rate variation on oil production and concluded that the recovery rate and ultimate recovery are not affected. However, nighttime steam is required for two primary reasons: health and safety to prevent backflow of hydrogen sulfide (H_2S) and maintenance and lifetime to limit thermal cycling of well casings. Without the use of storage, the requirement of nighttime steaming implies a limit to the total solar fraction, roughly 80% in the Gulf region.

The decision maker is faced with three different steam-supply sources and has to select a combination of them to suit the energy needs of the oil field. One can create a hypothetical example on the basis of the preceding discussion for an electricity-matched isolated oil field, where the marginal fuel cost is USD 6/million Btu. The decision maker will always select the most economic source of steam to fill as much of their supply as possible. At USD 6/million Btu, Solar is the lowest cost at USD 17/ton; next is the fully burdened Cogen at USD 20/ton; and, finally, the once-through steam generator is most expensive at USD 27/ton, and will supply the remaining steam demand. This is shown in **Fig 7.**

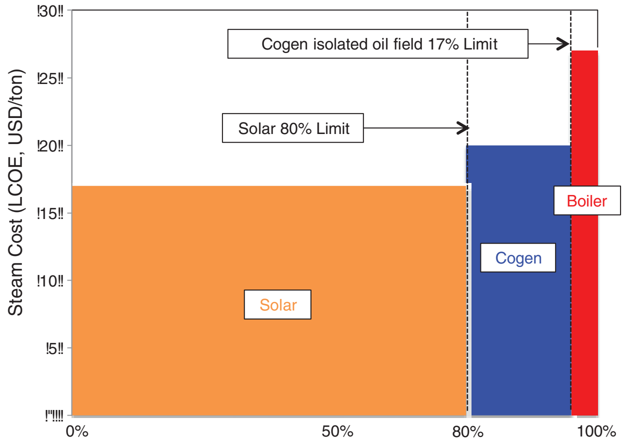

Fig. 7—Steam-supply curves for USD 6/million Btu fuel price.

Conclusions

Thermal-EOR projects provide very good ultimate recovery and increase production. However, the fuel-gas consumption is a problem. The thermal-EOR steam-generation projects in Gulf oil fields are on such a large scale that they affect an entire country's economic position. The field development may entail steam injection for many decades. Thus, the power/gas requirements have an important impact at a national level. Proper consideration of full economic cost and the future impact on gas consumption is essential.

Furthermore, the costs of the three methods of steam generation considered should be fully burdened to account accurately for the true macroeconomic implications. At a fuel price of USD 6/million Btu, Solar is the cheapest method of steam generation at USD 17/ton. Next is the fully burdened Cogen at USD 20/ton. The most expensive source is the fully burdened Boiler, which is USD 27/ton.

Finally, the limitations of Cogen steam as a result of the oil field's electrical/thermal demand ratio will determine the ideal steam-supply curve on the basis of the marginal fuel cost.

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Appendix A: Detailed Performance Modeling

The CCPP and Cogen systems analyzed in this paper both rely on heavy-duty GT engines from General Electric (GE) to obtain the waste heat they use to generate steam. GT performance is heavily dependent on the prevailing ambient conditions, particularly ambient temperature. **Tables A-1 and A-2** show the impact of ambient temperature on the performance of the GE 9E.03 (PG9171E) and 9F.05 engines that were chosen for our analysis.

The GE 9E.03 was chosen as the prime mover for the Cogen because of its use in similar projects around the world and its ability to produce approximately 6,000 tons/D of steam of 100-bar, 80%-quality EOR steam. The GE 9F.05 was chosen as the prime mover for our reference 2×1 CCPP because it represents a PP with

GE 9E.03 Performance Data

	15°C	40°C	Units	59°F	104°F	Units
Net power	130,000.0	108,506.0	kW	130,000.0	108,506.0	kW
Heat rate (LHV)	10,403.0	10,933.0	kJ/kW-hr	9,860.0	10,362.0	Btu/kW-hr
Heat cons. (LHV)	1352.4	1186.3	GJ/h	1281.8	1,124.4	million Btu/hr
Exhaust flow	1496.8	1330.7	$\times 10^3$ kg/h	3,300.0	2,934.0	$\times 10^3$ lbf/hr
Exhaust temperature	541.7	560.0	°C	1,007.0	1,040.0	°F

Table A-1—Impact of ambient temperature on the performance of GE 9E.03.

GE 9F.05 Performance Data

	15°C	40°C	Units	59°F	104°F	Units
Net power	299,000.0	235,660.0	kW	299,000.0	235,660.0	kW
Heat rate (LHV)	9295.0	9880.0	kJ/kW-hr	8810.0	9364.0	Btu/kW-hr
Heat cons. (LHV)	2779.2	2328.2	GJ/h	2634.2	2206.7	million Btu/hr
Exhaust flow	2400.2	2075.9	$\times 10^3$ kg/h	5292.0	4577.0	$\times 10^3$ lbf/hr
Exhaust temperature	643.5	657.2	°C	1190.0	1215.0	°F

Table A-2—Impact of ambient temperature on the performance of GE 9F.05.

Annual fuel consumption	9,378,095 million Btu/yr
Annual steam production	2,192,081 t/yr
Annual net electricity production	882,079 MW_{he}/yr
Net GT average annual net LHV efficiency	32.4%
GT average net LHV heat rate	10,538 Btu/kW-hr

Table A-3—Cogen heat-balance model results with GT at 85% load.

Annual fuel consumption	10,598,238 million Btu/yr
Annual steam production	2,332,579 t/yr
Annual net electricity production	1,040,334 MW_{he}/yr
Net GT average annual net LHV efficiency	33.8%
GT average net LHV heat rate	10,104 Btu/kW-hr

Table A-4—EOR Cogen heat-balance model results with GT at 100% load.

a net LHV efficiency of slightly more than 58%, which is comparable to the efficiency of recently built CCPPs in the GCC region.

As a result of the impact that ambient conditions have on GT power, heat rate, exhaust-flow rate, and exhaust temperature, a model that can predict the response of the entire plant is needed to assess plant performance accurately on an annual basis. We used the EBSILON®Professional heat- and mass-balance software from STEAG Energy Services in Germany in conjunction with the VTU Energy OEM Gas Turbine library add-in for EBSILON to build steady-state heat- and mass-balance models of a Cogen boiler and a 2×1 CCPP. These models were then run to predict fuel consumption, electricity output, steam production, and other key parameters for every hour of a year by use of hourly TMY3-format ambient-condition data for Amal, Oman. We chose Amal as the reference point because we have solar-performance data from that site and wanted to make sure all methods of steam generation are compared at the same location. The key results obtained from these model runs are detailed in **Table A-3.**

The results in Table A-3 are for 100% availability. In the LCOE model, we applied an availability of 92%, bringing the total annual steam production down to 2,016,715 t or 5,525 tons/D. Also, the Cogen model assumes an operation at 85% load, which is common practice in the oil field. We also ran the Cogen model at 100% load, and the results are shown in **Table A-4.**

The Cogen model is an unfired system with a low-pressure economizer section and recirculation to keep the stack temperature above the sulfuric acid dewpoint. The design point was chosen so that the Boiler could produce 75.7 kg/s of 100-bar 80% exit-quality steam with 5°C ambient air and 55°C produced water from the oil field. The EBSILON process-flow diagram from the model is shown in **Fig. A-1.**

The EOR Cogen model incorporates the following assumptions:

- Feedwater for EOR Cogen is always 55°C.
- EOR Cogen exit quality is always 80%.
- Water leaving the EOR Cogen's economizer section is recirculated to its inlet to maintain an economizer water-inlet temperature of 135°C to prevent sulfuric acid condensation on the economizer tubes.
- There is no preheating of incoming natural gas.
- Fuel to the GT is sour natural gas, containing 4 ppm H_2S and with the composition detailed in **Table A-5.**

An EBSILON heat- and mass-balance model of an unfired, 2×2×1 (2GTs/2HRSGs/1ST) CCPP was constructed on the basis

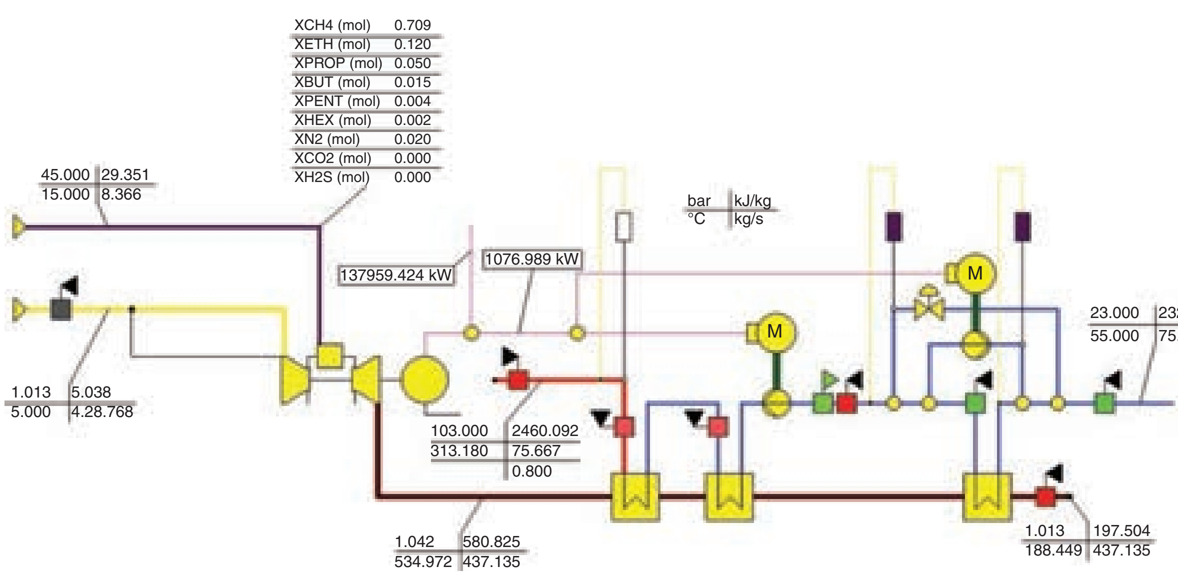

Fig. A-1—EBSILON model of EOR Cogen.

Constituent	mol%
Methane (CH_4)	79.0
Ethane (C_2H_6)	12.0
Propane (C_3H_8)	5.0
n-Butane (C_4H_{10})	1.5
n-Pentane (C_5H_{12})	0.35
n-Hexane (C_6H_{14})	0.15
Nitrogen (N_2)	2.0
Carbon Dioxide (CO_2)	0.01

Table A-5—Composition of sour natural gas that fuels the GT in the EOR Cogen model.

Plant net output	890 $MW_{electrical}$
Plant net heat rate (LHV)	5,865 Btu/kW-hr
Plant net efficiency (LHV)	58.2%

Table A-7—Plant performance at ISO conditions (15°C, 60% relative humidity, and 1.013 bara). ISO = International Organization for Standardization.

of the GE 9F.05 300-MWe-class heavy-duty GT engines. The plant uses two unfired, three-pressure-level (high pressure, intermediate pressure, and low pressure) reheat heat-recovery steam generators to raise steam for a single, 305-$MW_{electrical}$ condensing-steam turbine with once-through seawater cooling. The basic design parameters **(Table A-6)** for this plant were chosen from experience and some GE reference papers (Chase and Kehoe 2000; Tomlinson and McCullough 1996) on GE's Steam and Gas PP product line. The plant's process-flow diagram is shown in **Fig. A-2.**

Annual fuel consumption	42,689,075 million Btu/yr
Annual net electricity production	7,147,863 MW_{he}/yr
Plant average annual LHV net efficiency	57.12%
Plant average annual net LHV heat rate	5,974 Btu/kW-hr

Table A-6—2×1 GE 9F.05-based CCGT heat-balance-model results.

The CCGT model incorporates the following assumptions:

- Main steam conditions of 1,815 psia/1,050°F or 125 bara/565°C.
- Hot reheat steam conditions of 390 psia/1,050°F or 27 bara/565°C.
- Design point condenser pressure of 2 in. HgA or 68 mbar.
- Natural gas to GTs is preheated to 365°F (185°C).
- Cooling-water temperature for the CCGT plant's condenser was assumed to be ambient temperature (+10°C) unless that would place it at more than 35°C or less than 20°C, in which case it was pegged to either 20 or 35°C.
- Design-point cooling-water temperature rise of 20°F (11°C).
- Natural-gas composition for the CCGT model was the same as that for the EOR Cogen model.
- The plant performance at ISO conditions (15°C, 60% relative humidity, and 1.013 bara) is shown in **Table A-7.**

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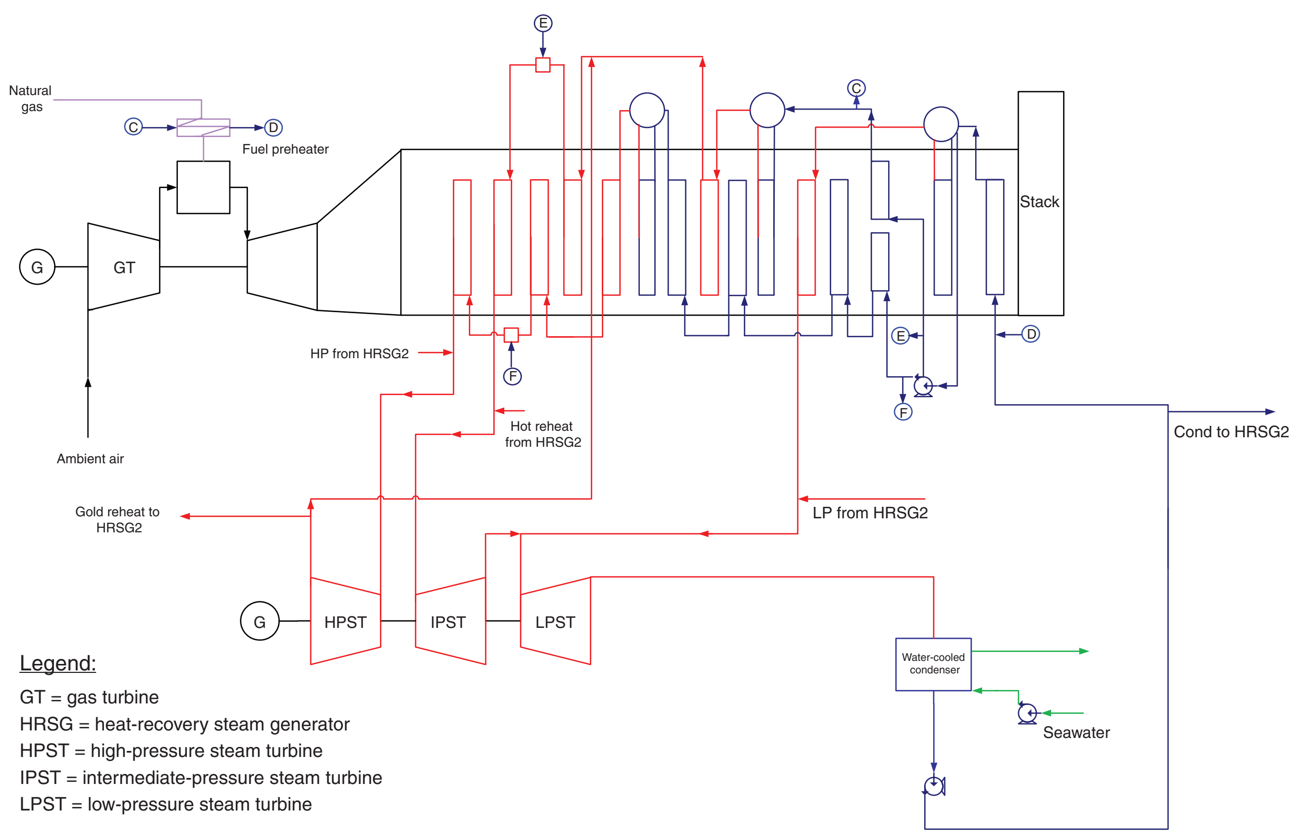

Fig. A-2—Plant-process-flow diagram.

and Water division. Chaar's renewable-energy experience started with Ausra (later Areva Solar) in 2008 and includes feasibility studies for solar in the United Arab Emirates and Saudi Arabia, as well as wind in Morocco. He holds master's degrees in mechanical engineering and business from Stanford University and Harvard Business School, respectively.

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