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Steam generation by solar and natural gas generators for thermal enhanced oil recovery

Abha Dwivedy

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Steam Generation by Solar and Natural Gas Generators for Thermal Enhanced Oil Recovery

Abha Dwivedy

Problem Report Submitted
to the College of Engineering and Mineral Resources
at West Virginia University

in Partial Fulfillments of the Requirements
for the Degree of

**Masters of Science in
Petroleum and Natural Gas Engineering**

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Abstract

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With easy oil recovered all across the world, the oil fields are depleting and extraction of heavy oil is becoming more important. The exploration and drilling of new fields is expensive and time intensive. With most of the oil remaining is heavy and viscous; Enhanced Oil Recovery (EOR) methods are followed. Thermal EOR is the most widely used method in which steam injection is the most popular. Every year natural gas is burnt to produce steam and this amount is increasing as heavy oil reserves are developing all across the world. With increase in technological advancements and goal of reducing carbon emissions, solar energy is used to produce steam for the injection. This technology is called solar wells. The main objective is highlighting the cost of steam produced by natural gas and solar wells and finding investment, installation, operation and maintenance costs of these generators. Further, analyzing these costs, recommendations are made if new technology (solar wells) is worth the investment.

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Chapter 1 INTRODUCTION

1.1 Overview

With the recent decline in the prices of oil that further lead to decline in domestic production and increase in imports, the field growth of the petroleum reserves cannot be overemphasized. To optimize reservoir development for better economic returns, reservoirs are periodically assessed for the hydrocarbon reserves. Field growth of existing fields by enhanced oil recovery (EOR) methods are crucial as they contribute to 90% of the additional reserves in the U.S. [1]. The primary recovery of reservoirs consists of natural flow and artificial lift, resulting in an oil recovery of only 5-15%. Upon dissipating natural pressure, secondary recovery is carried out by injecting fluids; this target to an additional recovery of 30%. Tertiary recovery consists of thermal EOR, chemical EOR and gas injection, which increases the oil recovery to more than 80% [2]. Total world crude oil resources account for around 9-13 trillion bbl. out of which two-third are heavy oil and bitumen deposits. Heavy oil has higher density, higher specific gravity and higher viscosity compared to conventional oil. The oil resources all around the world as per IEA (International Energy Agency) have 30% of conventional oil, 15% of heavy oil, 30% of bitumen and oil sand, and 25% of extra heavy oil. The viscosity of oil is generally described by the API gravity [3].

American Petroleum Institute developed API gravity, which is used to measure the relative density of various petroleum liquids. With lower API number, higher is the specific gravity and heavier is the oil [4]. The table below distinguishes the heavy oil, extra heavy oil and bitumen as per 12th world petroleum congress.

	API Gravity	Viscosity
Heavy Oil	10 ° – 22.3 °	100 – 10,000
Extra Heavy Oil	< 10 °	100 – 10,000
Bitumen	< 10 °	> 10,000

Table 1-1 Classification of Different Heavy Oil based on API Gravity and Viscosity [5]

Heavy oil compared to conventional oil has higher level of Sulphur. The lighter fractions are eradicated through natural processes. With higher proportion of asphaltic molecules and substitution of carbon network with nitrogen and oxygen, oil density increases [6]. The global heavy oil resources represented by barrels in place are shown in the figure below-

Figure 1-1 Global Heavy Oil Resources, Barrels in Place [5]

The total worldwide estimate of heavy hydrocarbon is 5.5 trillion barrels and four-fifth of these deposits is found in the western hemisphere. The oil supply can be improved if heavy oil and natural bitumen reserves are recovered [7]. Furthermore, the variety of these viscous oil with respect to API gravity for different countries are represented in the figure below-

Figure 1-2 Variety of Viscous Oils for Different Countries [5]

The thermal recovery process is divided into two types, steam based and combustion based. This research focuses on steam based injection which further consists of cyclic steam simulation (CSS), steam flooding, and steam assisted gravity drainage (SAGD) [8]. The new technological development in Thermal Enhanced Oil Recovery is solar powered oil field that

uses solar energy to heat water and convert it into steam. This steam is then injected into the wells for enhanced oil recovery.

1.2 Project Goals

This project focuses on the production of steam by Solar Steam Generator (SSG) and Heat Recovery Steam Generator (HRSG) for Thermal Enhanced Oil Recovery (TEOR), used by major oil companies. As SSG is a new technology in the petroleum market, the goal of this project is to lay some light on the cost of steam produced by two different generation systems and additionally analyze investment, installation, operation and maintenance cost of these generators. As the price of natural gas fluctuates from different countries to different time frame, range of natural gas prices is observed to further calculate the cost of steam. This range is compared to steam generated by SSG. Based on the heavy oil reserves and annual solar radiance, most suitable locations are proposed, where SSG is suitable to operate. Finally, with this project, recommendations are made to oil companies, if this new technology (SSG) is worth the investment, considering both advantages and disadvantages.

Chapter 2 LITERATURE REVIEW

2.1 Concept of Thermal Enhanced Oil Recovery

As heavy oil is viscous and hard to flow, Thermal Enhanced Oil Recovery (TEOR) is carried out. Depending on the reservoir, API gravity of heavy oil is usually less than 20 degree and external heat is required for its production [8]. The process of thermal recovery is divided into two types firstly, hot fluid recovery in which fluid such as steam is injected in the reservoir and secondly, combustion recovery process in which the heat is generated within the reservoir. This project focuses on steam based injection as it is the most commonly used method. The injection of steam lowers the viscosity of oil as the crude oil is heated and thereby vaporizing the oil to increase the mobility and production. Furthermore, this effect reduces the surface tension, increases the permeability and improves the seepage condition of the reservoir. In shallow reservoirs, steam injection is the most economical way to obtain high viscosity crude. Some examples of shallow reservoir include San Joaquin Valley of California, oil sand of Alberta, Canada etc. [9].

2.1.1 Factors Affecting Thermal Enhanced Oil Recovery

The factors affecting the recovery of oil include viscosity reduction, steam distillation, thermal expansion, relative permeability, steam drive and alteration in capillary pressure.

2.1.1.1 Viscosity

The viscosity reduces with the change in temperature as shown in the figure below.

Figure 2-1 Viscosity of Different Oils at Different Temperatures [10]

The effect of temperature on viscosity depends on volatility, nature and composition of oil. With increase in temperature, the macromolecular structure of crude oil changes, causing monomers to be scattered. This results in improved flow property and decreased oil flow

resistance [11]. The viscosity reduction is explained by mobility ratio that is the ratio of effective permeability to viscosity [12]. Viscosity measures the resistance of oil to flow. With higher viscosity of oil, greater pressure drop is required to move oil through sand. As viscosity of water in formation and injection well is identical and lower than that of crude oil, it flows more readily through sand and pushes oil towards production well. The API gravity is measured for every kind of crude oil as it correlates to physical properties [13]. The equation below highlights the importance of change in viscosity to pore scale capillary effect. The v represents interstitial velocity, μ is fluid viscosity and γ is interfacial tension (IFT) between the displaced and displacing fluid. When pore scale capillary effect increases, viscosity also increases however, interfacial tension decreases.

$$Ca = \frac{v \times \mu}{\gamma} [14]$$

2.1.1.2 Steam Distillation

With high temperature steam, lighter fraction of crude oil is vaporized and this process is known as steam distillation. These lighter hydrocarbons are carried by the steam, combustion gas, hot water and distilled solvents in front of the combustion front, towards the production well [15]. Steam distillation is a critical function responsible for gravity segregation of fluids and low residual oil saturations in porous media. Through distillation process, oil composition has greater effect on efficiency of oil recovery than API gravity [16].

2.1.1.3 Relative Permeability Alteration

The relative permeability of oil, water and gas can be affected by high temperature and pressure of steam. The temperature can be altered by interfacial tension (IFT) between flowing phases or altered by the wettability of porous material. With increase in temperature, IFT between oil and water decreases and the wettability can shift to oil wet or water wet condition depending on fluids in the reservoir and porous media chemical composition. The IFT should be equal or less than 0.1 dyne/cm for relative permeability to be substantial and this is possible with light oil at very high temperature [17].

2.1.2 Properties of Steam

The steam injected through injection well is a mixture of vapor and liquid. The weight fraction of vapor is called steam quality. As vapor can sustain more energy than liquid, quality of steam is better if it has more amount of vapor. The heat from the steam heats cap rock, reservoir rock and base rock. At the initial step, hot vapor rises up due to low density and steam chest is

formed at the top of the reservoir. As oil drains downwards, the saturation reduces to approximately 5%. The condensed water and low viscous oil drains towards the production well and heats the high viscous oil at the bottom. The hot water displaces oil at the bottom of the reservoir. As water has lower energy than vapors and is more viscous, it moves slower than steam and leads to low effectiveness of oil production. Thus, gravity affects fluids more at the top of the reservoir than at the bottom.

Figure 2-2 Steam Chest and Heated Oil Zones in Steam Drive [18]

The water carries very large amount of heat per unit mass as it has highest specific heat and latent heat of vaporization than any other fluid. The variation of boiling water and dry saturated steam is shown in the figure below. The latent heat of vaporization is the difference between two curves and is higher at low pressure. It reduces to zero at 705 °F and 3206 psia, which is the critical point. Steam carries more heat than hot water at 100 to 1500 psia, where most of the projects operate.

Figure 2-3 Heat Content of Boiling Water and Saturated Steam at Different Pressure

Steam temperature increases with increase in pressure. At lower pressure, steam injection applications have low heat loss as heat loss decreases with low temperature. Additionally, deeper high pressure reservoirs and low permeability reservoirs experience higher heat loss as they require high injection pressures. Steam heats the formation when it gives up its lateral heat at constant temperature to turn into water. If the lateral heat is higher, steam can remain at higher temperature to heat the subsurface formations to move through the reservoir. From the above figure, the average condition of 80% quality steam required for injection is 450 degree Fahrenheit and 414.7 psia [10].

2.1.3 Steam Based Injection

The steam simulation process is applied to viscous oil and involves injection of steam into the reservoir through injection wells. To force the steam into the reservoir, the injection pressure must exceed the formation pressure. After the injection process, the reservoir is left for soak in period before oil is pumped out from the production well. The injected steam reduces the viscosity of heavy oil, making it easier to flow. Steam stripping is a process which removes larger fraction of crude oil by removing low boiling point liquids from heavy oil. With this process the constituents of oil remain the same with heavy components in the reservoir and favorable lighter fractions recovered from the production well. Upon the condensation of steam, stripped components condense to form solvent and increase the displacement efficiency. The

steam distilled is composed of naphthenic and aromatic components, which acts as a good solvent to oil. The paraffin aids the deposition of asphaltic component in front of steam, thereby restricting the oil flow from production well. Low recovery of the heavy oil can be caused by the shrinkage of the volatile condensing front as steam continues to pass. As the volatile constituent increases in the conventional oil from residual oil, the recovery rate decreases. The process of stripping, distillation and condensation of steam in general increases the rate of recovery favorably more than just the reduction of viscosity alone. The process of the injection from one or more well is called steam drive and this technique is effective for the recovery of heavy oil that has little success rate due to the difficulty of making a connection between production and injection well. When the flow path is heated, the steam moves to the oil zone and the oil drains towards the production well. If the well is poorly insulated or when the injection rate is low, hot fluid suffers a great heat loss. The temperature of non-condensable injected fluids is lower than that at the wellhead, causing the vapors to condense due to the heat loss. As heat is not maintained in steam, oil comes in contact with the hot water instead of steam. This can have an adverse effect on the initiation and rate of growth of steam zone and thereby on the recovery rate of the oil [19].

2.1.3.1 Cyclic Steam Stimulation

The cyclic steam simulation/injection (CSI) is a type of the steam based thermal recovery that uses viscosity reduction, gas expansion and wettability alteration. This process is applied to both heavy oil and light oil reservoir and was first introduced in late 1950s. To further increase the effectiveness, this process includes chemical additives, introduced in the horizontal wells and implemented in with hydraulic fracturing. The advantage of this method is that it gives quick payoff with high success rate. With respect to other steam recovery methods such as steam flooding (50-60% OOIP) and SADG (60-70% OOIP), this is less competitive. This process is also referred to as “huff-and-puff” as it involves periodic steam injection. One well is used as injector and producer with three stages of the cycle including injection, soaking and producing. Upon injection of steam into the well for certain period of time, temperature in the surrounding reservoir rises (200-300 degree Celsius under 1MPa of injection pressure). After the desired amount of steam is injected, the well is shut down to soak the steam for not more than few days. After the well is opened, the oil flows out with the built in pressure and then by artificial lift. This process of injecting, soaking, and producing is repeated until desired economic level is

achieved [20]. The recovery factor for CSI ranges from 20 to 35% and minimum depth for this method is 1,000 ft [19]. Depending on the structure and type of the formation, the depth can vary. Therefore, for the method to be very effective, the formation should have thick pay zone of greater than 10 meters, oil saturation greater than 40% and porous sand greater than 30%. As the geology is important for steam distribution, unconsolidated sand with low clay is favorable. Additionally, 10 API gravity and viscosity of oil between 1000 to 4000 cp is considerable with permeability of at least 100 md. The three stages of CSI is demonstrated in the figure below.

Figure 2-4 Different Process Steps in Cyclic Steam Simulation

The ultimate recovery from CSI is relatively low to total oil in the reservoir. However, the ultimate recovery from steam drive is higher. As steam flooding and CSI alone are not so effective, steam flooding may follow CSI as CSI recovers heavy oil around single well bore and steam flooding recovers oil between the wells. In some cases to help increase the initial production, steam flooding wells are produced for 1 or 2 cyclic steam simulation. This also leads to high operating cost and high steam capital. CSI followed by steam drive is a good combination for accelerating crude production and ultimate recovery [20]. By adjusting the artificial lift and injection of steam rates, the fluids from each well can be used to optimize the production. To identify which sub formation zone is producing gas, oil or water, downhole fluids flow measurements can be used. The cyclic steam simulation and steam flooding are mostly used

on vertical wells. Recently, horizontal wells and vertical wells with multilateral branches have tried using these methods with advantages of reduced footprint while trapping large subsurface regions. In such cases, when heavy crude oil is present in the reservoir, steam drive is inefficient and steam injection rates are limited due to high resistance to flow between wells. Cyclic steam injection reduces the resistance near the wells and this improves the injection rate by reducing the resistance to flow between the wells during the steam drive. The heated zones can be connected when cyclic steam injection process is repeated to further reduce the flow resistance and improve the steam drive operability. Steam flooding, steam drive and CSI are all related to the cost of steam which is generated by natural gas. To improve the economics, the waste heat can be used for co-generation or electricity can be generated and sold. Alternative fuels such as coal, coke etc. can also be used to generate steam. This process can control the overuse of steam by redirecting the steam where heavy oil has not been produced and shutoff from zones that have been swept. The natural occurrence of the gravity overrides in every steam flooding process. The expansion of the steam occurs downward and the heated crude oil drains from the production well by gravity. In the further section it is described how the geometry of this is totally different from SAGD (steam assisted gravity drainage) however, the basics mechanism is same [19].

2.1.3.2 Steam Flooding

Steam flooding is a widely used advanced technology to enhance heavy oil reservoir and improves the performance of low permeability reservoir. It is a widely used technology for heavy oil reservoir as well as low permeability light oil reservoir [20]. The basic principle of this process is that high temperature steam is injected into the reservoir that heats up the formation and steam acts as driving force to push oil from the producing well. The lighter components in the crude is distilled due to the presence of the gas phase and carried with hydrocarbon compounds. At the condensation front, steam condenses the hydrocarbon compounds leading to the reduction in viscosity. The condensation of the steam makes the process efficient and increase the sweep efficiency. When compared to hot water drive, the recovery is significantly higher from steam [19].

Figure 2-5 Steam Process After Initial Cycle [21]

In steam flooding, there is a separate injection and production well. This process is continuous as steam is injected from the injection well to form saturated steam zone around the well bore. There are two steps to this process-

1. Direct Steam Stimulation- Steam stimulation of production well.
2. Indirect Steam Stimulation- To increase the production from other wells, steam is injected to increase steam drive [19].

2.1.3.3 Steam assisted gravity drainage

There are other processes one of them namely Steam Assisted Gravity Drainage Technology by which heavy oil crude and bitumen is recovered. In this process, two horizontal wells are drilled into the oil reservoir few meters (approximately 5 meters) above the other and advanced steam simulation is performed. The high pressure steam is injected into the upper wellbore to heat the oil and further reduce its viscosity. This heat drains the oil into the lower wellbore from where it is pumped out [19].

Figure 2-6 Cross Section of Steam Assisted Gravity Drainage [22]

The mixture of sand, water and bitumen is called oil sand [23]. As it is very viscous and cannot flow like conventional crude. It must be heated underground before it can be produced and processed. The Twenty percent of the oil sand reserves are close to the surface and can be mined to be extracted. However, 70% of the reserves are on an average of 1300 feet below the surface. So in order to extract these deep bitumen deposits, techniques such as SAGD must be used. The steam injection and oil production from the two horizontal wells happen continuously [24]. The top well injects steam, which further heats bitumen to be separated from sand and collects in the lower well with produced water. The mechanism of this process takes place in 3 steps namely, steam condenses at interface, condensate and oil flow to the bottom as a result of gravity, and chamber grows sideways and upwards due to the continuous injection of steam as showed in the figure below [25]. The bitumen and water produced from the wells is sent to the upgrading plant where bitumen is separated from the water. This water is recycled into the steam generator and injected back into the upper horizontal well [24].

Figure 2-7 Conceptual diagram of the SAGD process [25]

The difference between water's saturation temperature at producer pressure and actual temperature where pressure is measured is called sub cool. Sub cool is higher and temperature is lower if the liquid level is above the producer. As reservoirs are heterogeneous, it becomes challenging to achieve sub cool throughout the length of the horizontal well. Therefore, when uneven steam chamber development is faced, small quantity of steam enters the producer. This allows the bitumen to remain hot in the entire wellbore thus keeping its viscosity low and this allows transferring heat to the colder parts of the well. Also, when operator deliberately circulates steam in the producer following a shut in period, this process is called partial SAGD. With high value of sub cool, the steam injection and production slightly reduces due to high viscosity and lower mobility of bitumen at low temperature. The high steam pressure cannot sustain the steam chambers and can result in its collapse. With continuous injection and production at reservoir pressure, instability problems are even out and production rate increases to 70 to 80% of OOIP. SAGD is twice as efficient as CSS process and results in fewer well damages by high pressure. Additionally, it is even more economical as recovery rate of oil is higher. The formation with thin shale barriers produces the recovery rate of 60 to 70% [26].

2.2 Solar Generator for Thermal Enhanced Oil Recovery

Solar Enhanced Oil Recovery uses concentrated solar Energy to convert light energy into heat energy which further heats the water and converts it into steam. This steam is further heated up to 400 degree Celsius with pressure of 100 bar and is injected into oil well to reduce viscosity of heavy oil and makes it easier to recover [27]

The system has two main components namely, reflector and receiver. The reflector is the mirror that captures and focus sunbeam onto the receiver and receiver contains water which is

further heater to be converted into steam. The tracking system keeps the sunlight focused throughout the day on receiver. The solar power EOR systems also have thermal energy storage system that collects heat energy during the day and produce steam from water in the evening or during less sunny days [28]. On the other hand, hybrid systems using natural gas combined with solar powered steam generators supplement energy during low solar radiation period. With the help of solar EOR, steam is produced during morning hours when solar energy is available and gas fired steam is used during the night or less sunny days. With this process, large amount of natural gas consumption can be lowered without affecting the output of heavy oil.

2.2.1 Types

2.2.1.1 Central Tower-

Central tower also known as power tower technology uses heliostats, large tracking mirrors to focus concentrated sunlight onto the central tower receiver filled with demineralized water [29]. Sunlight can be concentrated upto 1,500 times onto water, which is used as the heat transfer fluid [30]. The reflected sun's energy heats up the water to produce high temperature and pressure steam. This steam passes through the heat exchanger into distribution heater and further to injection wells [31].

2.2.1.2 Linear Concentrating System

Linear concentrating system uses long U shaped mirror to focus sunlight on the receiver tubes that run through the length of the mirror. The fluid flowing through the tubes is heated with the concentrated sunlight and is sent to heat exchanger into distribution heater to injection wells. There are two types of linear systems namely- parabolic trough systems and linear Fresnel reflector systems. In parabolic trough system, the receiver is positioned along the focal length of mirror and has a parabolic shape. The mirrors can focus 30 to 100 times the normal intensity of sun light achieving a temperature of up to 750 degree Fahrenheit. There are three major plants in the U.S. - Mojave Solar Project in California, Solana Generating Station in Arizona, and Genesis Solar Energy Project in California. Linear Fresnel reflector system uses Fresnel effect to concentrate 30 times normal intensity solar rays to be concentrated onto mirrors with large aperture and short focal length. The receiver is placed above several mirrors to allow greater mirror mobility for tracking the sun with increased efficiency and reduced material cost and requirement. Linear concentrating systems are built aligned to north-south orientation to collect maximum solar energy and enable the tracking of sun from east to west during the day [28].

2.3 Natural Gas Generator for Thermal Enhanced Oil Recovery

Natural gas steam generators are used in oil fields to generate saturated steam from injection fluid into the reservoir for enhanced oil recovery. For the conversion of water into steam, the generators are installed with steam drums. The steam drum has centrifugal drum that uses centrifugal and inertia forces with the heat from the exhaust gas to convert water into steam. The superheated section then further heats the steam to the desired temperature [32]. Typical efficiency of natural gas steam generator is between 80-85% however, can increase to 90% with special equipment design. Typical capacity of steam generators range from 10^7 to 150×10^6 Btu/Hr. The corresponding rate of feedwater ranges from 650 to 10,000 BWPD (barrels of feedwater per day) recovering 80% quality steam. The size of the steam generator depends on the overall cost effectiveness [33].

2.3.1 Types

2.3.1.1 *Once through Steam Generators*

There are two types of gas steam generators namely Once through Steam Generators (OTSG) and Heat Recovery Steam Generators (HRSG). Once through Steam Generator (OTSG) is a special type of HRSG without boiler drums. OTSG are designed to have a continuous path for feedwater and does not have economizer, evaporator or superheater. As these generators are designed based on the heat load, they have high degree flexibility. With the absence of steam drum, there are fewer variables to control leading to quick change in the production of steam. In OTSG, hot exhaust gases can pass over the tubes with no water flowing inside with proper material selection. With this design, exhaust gas diverter system and bypass stack are eliminated [34]. The basic design of OTSG is shown in the figure below-

Figure 2-8 Once Through Steam Generators [35]

2.3.1.2 Heat Recovery Steam Generators

There are four main systems in Heat Recovery Steam Generators (HRSG) namely the preheater, evaporator, economizer and superheater. This generator can be categorized based on several variables such as the level of pressure or direction of exhaust gas and water. In horizontal HRSG, the exhaust gas flows horizontally over vertical tubes however, in vertical HRSG, exhaust gas flows vertically over horizontal tubes. The HRSG analyzed for this report has dual pressure system consisting of high and low pressure systems. There are steam generators that have single or triple pressure sections. Each section has steam drum that recirculates water and water-steam mixture to form saturated steam which is further converted into superheated steam. The figure below shows the design of HRSG [34]-

Figure 2-9 Cross Section of Heat Recovery Steam Generator [34]

2.4 Case Study

2.4.1 Aera Energy

Aera Energy has many oil fields where TEOR (Thermal Enhanced Oil Recovery) is performed such as South Belridge, Coalinga, Cymric, Lost Hills, McKittrick, Midway-Sunset, and San Ardo [36]. Kern County is the largest producing county for Aera Energy and includes Belridge, Cymric, Kern River, McKittrick, Midway-Sunset, and Lost Hill fields. The onshore operations are performed at San Ardo and Coalinga [37]. Heavy oil is recovered from Tulare formation and the company produces 75,000 barrels of oil per day from here. The south of Belridge is the 6th most and Lost Hill is the 9th most productive fields in the United States [38]. Coalinga is located in the Fresno County and produces approximately 6,000 barrel of heavy oil per day [39]. Midway Sunset field is located in the southwest of Kern County and ranks top 10 in the production of oil in the U.S [40]. San Ardo is located in the Monterey County and produces an approximate of 10,200 barrels of heavy oil per day [41]. The location of fields are shown in the figure below-

Figure 2-10 Different Areas of Operation by Aera Energy [42]

Additional information on the fields and EOR production is shown in the table below-

Field	Lease Operator	Fuel Type	Maximum Power Output (MW)	Surplus Power Buyer*	Approx. Plant Cost (\$ millions)	Fuel Requirements
Belridge S.	Aera	Gas	9.6	None	12.0	6.0 MMcf/d
Belridge S.	Aera	Gas	65.0	PGE	53.0	15.6 MMcf/d
Kern River	Aera	Gas	28.0	PGE	33.1	7.3 MMcf/d
Kern River	Aera	Gas	46.0	PGE	57.0	9.5 MMcf/d
Midway-Sunset	Aera	Gas	4.0	PGE	6.0	1.2 MMcf/d
San Ardo	Aera	Gas	6.2	None	8.2	3.8 MMcf/d

Table 2-1 EOR production at Different AREA Energy Fields [43]

The arrows marked on the table below represent the additional fields of the Aera Energy.

Operator	Field	State	County	Date Begun	Prod Wells	Inject Wells	Depth Ft	Total Prod BOPD	EOR Prod BOPD	Estim Power (hp)
AERA	Belridge	CA	Kern	Jan-61	2,900	975	400-1,400	37,000	37,000	27,750
AERA	→ Cat Canyon	CA	Santa Barbara	Mar-85			2,500-4,500			
AERA	→ Coalinga	CA	Fresno	Jan-80	190	22	825-1,650	3,580	3,580	2,685
AERA	→ Coalinga	CA	Fresno	Nov-87	172	48	650-1000	5,850	5,850	4,388
AERA	Cymric	CA	Kern	Dec-86	100	46	1,000	5,600	5,600	4,200
AERA	Kern River	CA	Kern	Jan-70	840	270	150-1,500	10,800	10,800	8,100
AERA	Lost Hills	CA	Kern	Jun-90	100	36	350	4,070	4,070	3,053
AERA	Lost Hills	CA	Kern	Jun-90	125	37	200	4,500	4,500	3,375
AERA	McKittrick	CA	Kern	Mar-88	145	115	600	4,500	4,500	3,375
AERA	Midway-Sunset	CA	Kern	Oct-70	381	32	950	12,000	12,000	9,000
AERA	Midway-Sunset	CA	Kern	Jan-79	66	0	900	800	800	600
AERA	Midway-Sunset	CA	Kern	Jan-89	78	8	800	1,600	1,500	1,125
AERA	Midway-Sunset	CA	Kern	Jan-83	205	25	1,080	4,300	4,300	3,225
AERA	Midway-Sunset	CA	Kern	Jan-71	650	34	500-1,400	6,600	6,600	4,950
AERA	Midway-Sunset	CA	Kern	Jan-80	145	8	1,300	2,200	2,200	1,650
AERA	→ Mount Poso	CA	Kern	Jan-71	75	16	1,500-1,800	3,100	3,100	2,325
AERA	North Midway-Sunset	CA	Kern	Nov-67	376	21	1,000	10,750	10,750	8,063
AERA	San Ardo	CA	Monterey	Jun-68	100	28	2,300	1,930	1,930	1,448
AERA	San Ardo	CA	Monterey	Mar-80	42	14	2,100	7,350	7,350	5,513
AERA	South Belridge	CA	Kern	Jan-69	510	263	1,000	43,200	43,200	32,400
AERA	South Belridge	CA	Kern	Jan-65	50		1,000	460	460	345
AERA	→ Yorba Linda	CA	Orange	Jan-71	203	11	500-1,000	1,000	750	563
ARCO	Kern River	CA	Kern	Jan-70	88	11	600	370	370	278
ARCO	Kern River	CA	Kern	Jan-70	87	28	1,200	1,000	1,000	750
ARCO	Kern River	CA	Kern	Sep-72	25	11	900	300	300	225
ARCO	Kern River	CA	Kern	Jan-72	80	39	800	800	800	600
ARCO	Midway-Sunset	CA	Kern	Jan-72	63	7	1,200	1,050	1,050	788
ARCO	Midway-Sunset	CA	Kern	May-05	137	13	1,500	3,500	3,500	2,625
ARCO	Midway-Sunset	CA	Kern	Jan-83	109	42	1,500	2,500	2,500	1,875
ARCO	Midway-Sunset	CA	Kern	Jan-81	94	13	1,200	1,250	1,250	938
ARCO	Midway-Sunset	CA	Kern	Aug-72	130	5	1,000	900	900	675
ARCO	Midway-Sunset	CA	Kern	Jan-84	7	0	1,300	120	120	90
ARCO	Midway-Sunset	CA	Kern	Jan-69	98	17	1,100	2,700	2,700	2,025
ARCO	Midway-Sunset	CA	Kern	Jan-89	127	4	1,500	1,750	1,750	1,313

Table 2-2 Additional Fields of EOR Operation by AERA Energy [43]

One of the parent companies, Shell holds 52% of EOR holding in AERA Energy and produces 100,000 barrels of oil through steam flooding in California [44]. The 96.5% of EOR operations worldwide are performed by steam generators out of which 65% occur in north of

America and out of which 94% occur in California's San Joaquin Valley. The oil recovered in San Joaquin Valley is 303,000 barrels per day using 768 OTSGs each averaging about 60 MMBTU per hour [45]. With the engagement of AERA and ClearSign in the installing of OTSG in Bakersfield, high energy efficiency was achieved at high firing rate and reduced NOx emission to less than 5 parts per million (PPM) [46]. For the production of steam, Aera is self-sufficient with the water supply. 99% of the water used in the EOR is recycled with the use of less than 1% of fresh water. Freshwater is used for dust suppression, equipment and process cooling, drilling, hydraulic fracturing, and domestic use [42]. Some of the specifications of EOR production in Aera Energy fields are shown in the figure below-

Midway Sunset Aera							
Operation	Equipment	HP Capacity (hp)	Units	Cum HP Capacity (hp)	Adj. HP Capacity (hp)	Adj. MW Capacity (mw)	Adj. MW Usage (mwh/yr) ¹
Fluid Lift	Rod Pump	30	1,525	45,750	45,750	34.13	269,077
Water Injection (Disposal)	Central Facility	2,000	20	40,000	40,000	29.84	235,259
	Individual Injection Wells	120	300	36,000	36,000	26.86	211,733
Total:				121,750	121,750	91	716,068
Co-Generation							
Operation	Units	Unit Fuel Requirement (mmcf/d)	Total Fuel (mmcf/d)	Unit Steam Generation (lbs/hr)	Total Steam Generation (lbs/hour)	Unit Capacity (MW)	Total Capacity (MW)
Electricity/Steam Generation	1	4.8	4.8	25,000	25,000	4	4
Total:			4.8		25,000		4

¹ Assumes 24hr/day, 328 days/year

Table 2-3 Different Operations at Midway Sunset, AERA Energy

This field produces 27,500 BOPD from 107 steam injection wells and 1525 production well. For the generation of electricity and steam, natural gas is used. The 4th highest expense of the operation is electricity and is purchased from local utility at \$0.043 to \$0.18KWH [43].

South Bellridge Aera							
Operation	Equipment	HP Capacity (hp)	Units	Cum HP Capacity (hp)	Adj. HP Capacity (hp)	Adj. MW Capacity (mw)	Adj. MW Usage (mwh/yr) ¹
Fluid Lift	Rod Pump	30	560	16,800	16,800	12.53	98,809
Water Injection (Disposal)	Central Facility	2,000	5	10,000	10,000	7.46	58,815
Total:				26,800	26,800	20	157,623
Co-Generation							
Operation	Units	Unit Fuel Requirement (mmcf/d)	Total Fuel (mmcf/d)	Unit Steam Generation (lbs/hr)	Total Steam Generation (lbs/hour)	Unit Capacity (MW)	Total Capacity (MW)
Electricity/Steam Generation	1	63	63	300,000	300,000	65	65
	1	6	6	175,000	175,000	9.6	10
Total:			69		475,000		75

¹ Assumes 24hr/day, 328 days/year

Table 2-4 Different Operations at South Bellridge, AERA Energy

For the above field, co-generated electricity is used for water disposal and fluid lift to generate useful heat and electricity at the same time. The steam generated and electricity produced on site is sufficient to carry out Aera's EOR process. As very little associated gas is produced from the field, the standby electricity is purchased from PG&E for \$0.20/kWh. The production of EOR depends directly on fluid lift and if it shuts down, production stops immediately. This operation is carried out at later stages when the artificial lift is used for the production to maintain reservoir pressure against pressure drop due to depletion [43]. The information of power generation and additional co-generation in major fields of California is summarized below.

Field	Projects	Power Capacity (MW)	Natural Gas Usage (MMcfd)	Cogenerated Steam Injected (MBS/D)	Total Steam Injected (MBS/D)	Percent Cogen/ Total
Kern River	10	812	220	371	371	100%
Midway-Sunset	10	415	121	281	478	59%
Kern Front	4	189	44	25	25	100%
Placerita	2	142	49	20	20	100%
San Ardo	3	82	24	53	53	100%
South Belridge	2	75	22	60	291	21%
Coalinga	5	59	22	65	87	75%
Mt. Poso	1	50	(coal-fired)	3	11	29%
Cymric	4	27	33	34	76	44%
Lost Hills	1	10	4	8	37	22%
Total (10 Fields)	42	1,861	539	920	1,449	63%
Total California TEOR	51	2,071	625	934	1,521	61%

Table 2-5 Summary of Cogeneration in California Fields [43]

2.4.2 Chevron

Chevron is an American multinational energy company that has various thermal EOR fields with leading capabilities such as reservoir simulation and laboratory testing in gas EOR clear[46]. Thermal EOR of Chevron operates in Kern, Fresno and Monterey County of California and Coat of Sumatra of Riau Province [43]. Chevrans Monterey County is the 4th largest producer of oil in California and oil field San Ardo includes various TEOR (Thermal Enhanced Oil Recovery) methods such as Conventional, Cyclic Steam Injection, Steam Flooding and Water Flooding. The field produces up to 180,000 barrels of water per day and the used water is recycled by reverse osmosis process and injected into wastewater disposal well. Reverse osmosis is used to remove toxic and volatile organic compounds such as radioactive substance, heavy metals, and hydrocarbons. Chevron now processes up to 66,700 barrels of wastewater in San Ardo facility and recovers 50,000 barrels of treated water. The treated water is released into

ponds under San Ardo field. The table below summarizes total production, EOR and other important details from each of the fields in chevron USA [47].

Operator	Field	State and County		Date	Prod well	Inj Well	Depth Ft	Total Prod and EOR, BOPD		Power, hp	
Chevron	Cymric 26W	CA	Kern	Oct-89	31	19	1,200	1,461	1,461	1,096	Succ.
Chevron	Cymric 35/36W	CA	Kern	May-75	130	47	1,200	6,518	6,518	4,889	Succ.
Chevron	Cymric 5Z	CA	Kern	Feb-91	14	4	1,200	591	591	443	Succ.
Chevron	Cymric 6Z	CA	Kern	Feb-86	31	19	1,200	900	900	675	Succ.
Chevron	Cymric 7Z	CA	Kern	May-91	30	30	600	70	70	53	Succ.
Chevron	Kern River-ANO	CA	Kern	May-74	177	82	1,000	3,643	3,643	2,732	Succ.
Chevron	Kern River KCL 39	CA	Kern	Oct-75	67	42	1,400	379	379	284	Succ.
Chevron	Kern River MC1	CA	Kern	Apr-76	120	76	960	2,072	2,072	1,554	Succ.
Chevron	Kern River MCII	CA	Kern	Apr-71	129	30	960	2,274	2,274	1,706	Succ.
Chevron	Kern River Sec. 3	CA	Kern	Sep-68	345	155	775	8,340	8,340	6,255	Succ.
Chevron	Kern River Sec. 4	CA	Kern	Jun-78	200	64	850	3,778	3,778	2,834	Succ.
Chevron	Kern River Sec. 9 HHF	CA	Kern	Jan-92	8		800	158	158	119	Succ.
Chevron	Midway-Sunset Sec. 15A	CA	Kern	May-78	36	5	1,400	1,600	1,600	1,200	Succ.
Chevron	Midway-Sunset Sec. 26C	CA	Kern	Nov-75	243	81	1,300	7,381	7,381	5,536	Succ.
Chevron	Midway-Sunset Sec. 2F	CA	Kern	Oct-83	44	10	1,800	2,251	2,251	1,688	Succ.
Chevron	West Coalinga 12-D	CA	Fresno	Feb-82	89	31	1,600	617	617	463	Succ.
Chevron	West Coalinga 13-D	CA	Fresno	May-73	182	104	1,200	2,465	2,465	1,849	Succ.
Chevron	West Coalinga 25-D	CA	Kern	May-80	131	95	2,500	5,441	5,441	4,081	Succ.
Chevron	West Coalinga 31A/36Z	CA	Fresno	Mar-89	70	21	1,700	1,382	1,382	1,037	Succ.
Chevron	West Coalinga 6C	CA	Fresno	Jul-84	131	18	1,500	689	689	517	Succ.

Table 2-6 Thermal EOR Projects for Chevron in California [43]

Kern County is the 5th largest producer in the U.S. With production continuing for 100 years, Chevron still continues to extract oil with the EOR technology. 70% of the chevron production in Kern County is with steam flooding. The recovery factor in kern valley is 60% compared to a global recovery of 32-35%. The recovery factor is percentage of original oil in place that is recovered. In primary recovery, the oil recovered from Kern is only 5-10% however, with hot water injection it raises to 15-25%. Furthermore with steam flooding the recovery can be achieved up to 80% [48]. Additional information on the fields and EOR production is shown in the table below-

Field	Lease Operator	Fuel Type	Maximum Power Output (MW)	Surplus Power Buyer*	Approx. Plant Cost (\$ millions)	Fuel Requirements
Coalinga	Chevron	Gas	5.8	PGE	6.6	2.8 MMcf/d
Coalinga	Chevron	Gas	5.8	PGE	5.5	2.8 MMcf/d
Coalinga	Chevron	Gas	5.8	PGE	6.0	2.8 MMcf/d
Cymric	Chevron	Gas	10.8	PGE	10.0	4.8 MMcf/d
Cymric	Chevron	Gas	6.0	PGE	5.5	2.1 MMcf/d
Cymric	Chevron	Gas	6.0	PGE	5.0	2.7 MMcf/d
Kern River	Chevron	Gas	42.0	PGE	32.5	11.8 MMcf/d
Midway-Sunset	Chevron	Gas	12.5	PGE	10.0	7.2 MMcf/d

Table 2-7 Cogeneration Facility for Chevron in California [43]

As steam flooding is very effective, it comes with a price of transporting natural gas and co-generation plants for the generation of steam and electrical power. The total energy consumed by co-generation plants is 62 million BTU which is equivalent to energy generated from 11 barrels of oil. This energy is used to generate 1,321 MW of power out of which Kern project

consumes 550 MW and rest is sold to power grid or used as a standby capacity. The reservoirs in Kern uses 180 kbpd of steam for the injection and additional cold water seeps through the surrounding rock that comes up into the pumps as oil strained water. This results in the production of 75 kbpd of oil, and 780 kbpd of water. The average oil production from Chevron Kern County is 8 bpd and median production is 6 bpd [48]. Chevron partnership with Indonesia goes back to 88 years and it accounts to 40% of nation's crude oil from Sumatra [49]. It uses steam flooding at its field North Duri Development Area 13 located in Sumatra, Indonesia and produces 185,000 barrels per day. The field extends to an area of 324 sq. km and is considered largest steam development in the world. In 2015, 77 percent of the field was deployed with steam injection with majority of Chevron Pacific Indonesia production coming from Duri field. The NDD Area has 539 new wells including 145 steam injection and 36 temperature observation wells. This is expected to increase 17,000 barrels of production per day [50].

Table 2-8 Chevron Solar EOR in California [51]

According to the recent report by SBI, this has added an additional estimate of 241.7 barrels of oil increasing the recovery to 70-90% [52]. The project extends to an area of 65 to 35 acre and consists of 3,822 mirror system (heliostats) of 10 by 7 foot on a steel pool of 6 foot. There are 7,644 mirrors in total focusing light on 327 foot of solar tower. The receiver on the solar tower captures solar rays and the heat produces steam for EOR. The steam generated is about the same as produced by one gas-fired steam generator [53].

2.4.3 Berry Petroleum

Berry Petroleum Company is an energy company primarily based out of California and is involved in production, development, acquisition, exploitation and exploration of crude oil and

natural gas since 1985. The world's first commercial Solar Enhanced Oil Recovery (EOR) unit was setup by Glasspoint inc at Berry Petroleum's 21Z lease in Kern County, California. The system adopts sun's concentrated sunlight to produce 1 million Btu per hour of solar heat thereby reducing the gas consumption from oilfield [54].

Figure 2.12: Berry Petroleum Thermal EOR Field at California [55]

Local oil producers in Kern County were seeking advanced technologies to economically produce from their heavy oil reserves which have been in production for over a century. Glasspoint partnering with local firms TJ cross engineers and PCL industrial services integrated the solar EOR system with existing facilities. This generates steam and preheated water at 190°F which is used as feedwater for the field's gas-fired generators. The efficiency and success of the first ever solar EOR unit at Berry petroleum helped GlassPoint solar land a contract to build a 7MW solar EOR for Petroleum Development Oman (PDO), the national oil company of Oman [56]. The glasspoint solar EOR system uses concentrated thermal energy from the sun thereby reducing the amount of natural gas burned for thermal EOR, releases gas for higher value applications, including power generation, desalination, industrial development and export. The resulting low-cost, emission free steam is fed directly into existing PDOs steam distribution network spanning more than 4 acres and producing 11 tons of high temperature (312 °C), high pressure (1,450 psi) steam per hour. The project at PDO is an estimated 27 times bigger than the Solar EOR at Berry petroleum, California. Glasspoint employs a unique single transit trough (STT) technology that encloses lightweight reflective mirrors inside a glasshouse structure. This protects the system from dirt, dust, sand, and humidity and reduces the natural gas usage for EOR by almost 80% in regions that are sunny. The STT technology combines existing proven

technologies in high volume production worldwide with low-cost, light-weight components. This produces five times steam per acre than older power tower designs. Employing the solar EOR, Oman could effectively use gas for higher value applications thereby enabling other gas dependent industries to flourish [57].

Chapter 3 SYSTEM DESCRIPTION

3.1 Solar Steam Generator

For this given project, central tower is considered for the production of steam for thermal EOR. The system description of central tower is as follows.

3.1.1 Heliostats

Heliostat is the basic building block of central tower solar steam generator and consists of three major components namely drive, reflector module and structure. The control system commands drive that houses two motors. The motor enables heliostat to move in two different axes and track sun accurately throughout the day [58]. The pedestal supports the reflective surface that helps in the movement of heliostat about its elevation and azimuth axis. Fractional horsepower motor through gearbox drive helps in the movement about each axis [59]. The reflector module has mirror glass and metal frame attached to the drive. Heliostat is made of several glass mirror module panel with reflecting element of thin second black surface. Some of the heliostat uses thin reflective plastic membrane stretched over the hoop to protect it from the weather. This design is considerably less expensive and light weight however, cleaning and renewal is an important consideration. The mirror is slightly concave as glass mirror is supported by a backing substrate. This structure provide sturdy and rigid anchor to the heliostat. The individual panels on the heliostat are canted towards a point on the receiver. The focal length of the heliostat is equal to the approximate distance from receiver to the farthest heliostat [60]. The figure below shows backside of heliostat used at Solar One central receiver pilot plant in Barstow, CA.

Figure 3-1 Parts of Heliostat [60]

The drive of heliostat is made of aluminum die cast, sintered metal and molded plastic components. Steel components and robotic welding are utilized in the making reflector module for high quality and repeatability. The stable and rigid structure utilizes progressive die stamping with robotic welding of steel components [58]. The reflective mirror is multilayered with silver providing high reflectivity in solar spectrum range. Protective layer of copper applied next to silver with prime coat, intermediate and protective top coat. The thickness of the complete mirror is approximately 4 to 5 mm. The Figure below shows multilayers of the mirror used in a heliostat.

Figure 3-2 Multilayer of Mirror on Heliostat [61]

3.1.2 Receiver Tower

The receiver is located at the top of the tower where the incident sun light from the heliostat can be most efficiently intercepted. The energy from the heliostat is transfer into heating the fluid flowing inside the receiver. The most commonly used receivers are external receivers that has panel of vertical small tubes welded to the side of the cylinder. These vertical tubes are connected to the headers to supply fluid (water) from the bottom of each tube and collect heated fluid from the top. The figure below shows an external receiver with 24 panels each 13.7 m (45 ft.) high, consisting of 70-12.7 mm (1/2 in.) diameter tubes. Six of these panels preheat water and eighteen produce steam. This receiver is mounted on a tower of 77.1 m (253 ft.) height. These tubes are coated with black paint and are made of Incoloy 800. The total diameter of the receiver is 7 m (23ft.).

Figure 3-3 Sections of Receiver Tower

The height to diameter ratio of external receiver is 1:1 to 2:1. To reduce heat loss, area of receiver is kept to minimum. By knowing the operating temperature of the tubes and heat transfer capacity of the fluid, lower limit is determined. For example, if liquid sodium is used as heat transferring fluid, height and diameter of the receiver is approximately 15 m (49 ft.) vs 13 m (41 ft) with peak output of 380 MW (1.3×10^9 Btu/h). However, if water is used as the transfer fluid, twice the area would be required due to the lower heat transfer capabilities.

3.1.3 Tower Design

For the design of the tower, weight of the receiver and windage area are the most important factors. The height of the tower is cost dependent and ranges from 140 to 170 m (460 to 560 ft). The fluid choice affects the size and weight of the receiver on the top of the tower. The construction material for the tower is steel frame or concrete. Cost analysis indicate that concrete towers are cheaper for higher towers and steel frame towers are cost efficient for height less than 120 m (400 ft). The weight of the receiver on top of the tower ranges from 250,000 kg (550,000 lb) to 2,500,000 kg (5,500,000 lb) [60]. In places where this project is constructed and where high sand and dust is experienced, robotic cleaning system is installed. This uses high pressure water to clean mirror surface without coming in contact with the reflective mirror. With this technology, high temperature solar steam recovery is maintained by proving maximum reflective energy. This does not require an enclosed glass house and can be deployed on an uneven terrain with high reliability and simple operation [62].

3.2 Heat Recovery Steam Generator

3.2.1 Economizer

The first primary part of HRSG circuit is economizer. The capacity of the economizer is to bring feed water to an approach temperature close to saturation temperature at which maximum heat energy can be absorbed leading to efficiency and operational adaptability. They act like once through heat exchangers and can be intended for steaming or non-steaming. The ones used in HRSG are non-steaming based on water quality, boiler life, heat optimization and operational consideration. An economizer is called as steam economizer when absorption of heat energy from high exhaust gas flows across water to produce steam. The figure below illustrates the process occurring in an economizer. Section of the economizer is made out of finned tube surface modules including drains and vents. These modules are arranged parallel to reach desire capacity and water temperature. The Drum control helps economizer to achieve water flow rate control [63].

Figure 3-4 Side Section and Cross Section of Economizer [64] [65]

Based on the pressure system of HRSG, there can be a single or dual economizer in the circuit. In dual pressure HRSG, there is a high pressure economizer and in three pressure HRSG, there is high and intermediate economizer. In high pressure economizer, each module is single pass on gas side and multipass on water side. The feed water received by feed pump absorbs heat from exhaust gas raising the water temperature to near saturation further directing it to the high steam drum [63].

3.2.2 Steam Drum

Steam drums operating in HRSG are equipped at high, intermediate and low pressure and are used for steam water separation, water storage and purity of steam control. The riser tube allows the steam water mixture to enter the drum and has approximately 5-10% of steam depending on the pressure and load of the boiler. The low percentage of steam in the mixture prevents the boiler tubes from overheating and leading to failure. When the mixture comes to the steam drum, the saturated steam separates from the mixture and rises to the top of the drum. The remaining water with feedwater from economizer enters the evaporator where heat is absorbed by the water from evaporator tubes. The steam water separation occurs with the combination of mechanical components and gravity. The separation of this mixture depends on the distinct level in the drum called as normal water level. There are two steps by which this separation occurs. In primary separation, centrifugal separator removes almost all the water however; some water traces are left which has to be removed before steam goes to the superheater. For that purpose,

secondary separation or steam scrubbing is carried out. The cyclone separator in primary separation is cylindrical in shape and is placed inside the drum along its length. With the rise tubes, the mixture enters this separator tangentially and the centrifugal force throws water against the cylinder wall. As water is denser than steam, the water flows down by gravity and steam moves to the center of the cylinder to rise above. The water discharges from cyclone separator through annulus. The steam passes through the corrugated scrubbers for secondary separation on the top of the cylinder. The scrubber removes any small amounts of contaminants and water. Steam drum contains control instruments such as relief valves, pressure indicator, riser pipes, downcomers and blowdown [63].

Figure 3-5 Cross Section of Steam Drum [66]

The high/low pressure drum gets feed water from high/low pressure economizer and mixes it with the water in the drum. Through the downcomers, water from the drum is fed to the bottom of high/low pressure evaporator. Natural loop is completed when steam and water steam mixture flows to steam drum through evaporator modules [63].

3.2.3 Evaporator

The steam generation and the boiling process occur in the evaporator. The heat energy from the gas stream is absorbed by water causing the temperature to increase. When this temperature reached the saturation temperature, water starts to boil and some of the water evaporates to steam. The water is fed into the evaporator through downcomer and the mixture of water steam leaves for steam drum via riser system. The continuous circulation of water entering the evaporator and leaving with a mixture of water steam is called natural circulation loop [63].

Figure 3-6 Cross Section of Evaporator [67]

3.2.4 Superheater

Superheater is the last component of steam generator circuit. It is used to increase the steam temperature above saturation. Steam cycle efficiency is improved as introduction of water into the injection well is minimized due to high temperature steam. The heat from the exhaust gas is absorbed by the superheater and this energy is transferred to steam. The section of superheater is made of finned tube surface modules with high metal temperature and arranged in parallel or series configuration to obtain desired temperature and capacity. Some water or condensate can be formed in the lower module header as a result of purge of warm start. This can be removed by drainable superheater. In the high pressure superheater, steam is received at saturated temperature from high pressure steam drum and heated to final steam temperature [63].

Figure 3-7 Cross Section of Super Heater [68] [69]

Chapter 4 MECHANISM

4.1 Steam Generation by Solar Power

Figure 4-1 Solar Steam Generation Mechanism

1. The heliostats are reflective mirrors that follow sun rays throughout the day.
2. The reflective mirrors capture the light energy from sun and convert it into heat energy.
3. At the top of the tower is receiver where, light is reflected from heliostats.
4. The water is converted into process steam and heated to high temperature with heat energy in the receiver.
5. The process steam is directed to heat exchangers at the bottom of the tower.
6. Inside the heat exchangers, the close loop system of pipe holds water obtained from oil production. The heat of process steam converts water into steam which is called saturated steam.
- 7a. The saturated steam is sent to the distribution system where it is sent to oil fields and injected into the reservoir through injection wells.
- 7b. Process steam cools down, becomes water and is sent to the boiler unit at the top of the tower into the receiver and this entire process is repeated [70].

4.2 Steam Generation by Natural Gas

Figure 4-2 Heat Recovery Steam Generation Mechanism [71]

Heat Recovery Steam Generators (HRSG) is basically a heat exchanger that absorbs and recovers heat from the exhaust gas stream to generate 1150 psia and 515 degree Fahrenheit steam. This steam is then directed to injection wells to be injected into the reservoir for the thermal enhanced oil recovery. As per the above figure, the numbers in the mechanism below are based on the flow path.

1. There are two flow paths in HRSG firstly, gas flow that starts from combustion turbine outlet to distribution grid (1) and finally to outlet stack (14). Secondly, water flow that starts from feed water pre-heater and moves through gas flow path to be converted into steam. This steam is directed to injection wells through high pressure steam outlet.

2. The gas flows across the duct burner (2) typically located between HP superheated sections (4), where gas is burnt and temperature reaches to 1500 degree Fahrenheit.
3. Observation port (3) provides complete assess to burner, furnace and convention section.
4. Feed water preheater (12) is where condensate water enters to be preheated and directed into low pressure steam drum (17). In the LP steam drum, preheated water mixes with the water (already in the drum) and leaves for low pressure evaporator (13) via downcomers.
5. Low pressure evaporator (13) is the place where steam is generated. This steam enters the LP steam drum again where separation between water and steam occurs. The recirculation between water-steam mixture and water produces saturated steam. This steam exits the steam drum to enter the high pressure superheater where it is heated to final steam temperature.
6. High pressure economizer (10) gets feed water from LP drum. The control valves control the entry of this water into HP steam drum (15) from the economizer. In the HP steam drum, feedwater mixes with the water (already in the drum) and leaves for high pressure evaporator (9). High pressure evaporator generates steam and this steam enters the HP steam drum. Recirculation produces saturated steam and transferred to high pressure superheater (4).
7. High pressure superheater absorbs the heat energy from the exhaust gas and increases the temperature of the steam making it superheated.
7. The superheated steam (4) is then routed to injection wells.
8. High pressure vent silencer (14) reduces the unwanted noise in the pipelines created by high velocity flow of stream or gas.
8. SCR catalyst (6) is made of ceramic elements that are compact, homogeneous and honeycomb structure. They are mixture of titanium dioxide, tungsten oxide, and vanadium pentoxide. The temperature in this section ranges from 635 to 675 degree Fahrenheit.
9. Selective catalytic reduction (S.C.R) system (8) removes NO_x (NO and NO₂) with Aqueous ammonia (NH₃) as reducing agent [63].

Chapter 5 CHAPTER V. METHODOLOGY

5.1 Steam from Solar Powered Generator

As the heat energy converts water to steam, following methodology is used to calculate total heat in BTU/Hr. required to further convert 10 gals of cold water to steam at 450 degree Fahrenheit and 414.7 psia.

Heat to raise water temp to boiling point → Heat to convert water to steam → Heat to increase the temperature and pressure of steam

1. If the available solar power density is 1.0 kWh/hr/m^2 , a solar collector can absorb 3412 BTU/hr/M^2 . Power available from the sun, as stated above, can be expressed in terms of BTUs per hour per square meter (btu/hr/m^2).
2. When water is boiling in a closed container, the temperature of the steam will not increase as heat is added until all the water in the container has turned to steam. Heat required to convert water from its boiling temperature to steam is called the Latent Heat of Vaporization and has a value of 970 BTU/lb for water at atmospheric pressure. What this means is for every pound of water, 970 BTU is needed to convert water into steam at $212 \text{ degree Fahrenheit}$. Heat of Vaporization for water equals 970 BTU/lb [72].
3. As the steam condition at the surface is 450 degree F and 414.7 psia , it is important to know the energy in BTU/hr to produce steam at the given conditions. For this, superheated steam table is used with safety factor assuming to be 1.2 and 80% quality of steam is produced

5.2 Steam from Natural Gas Powered Generator

1. Steam table at operating pressure of 1150 psia and feed water temperature at $515 \text{ degree Fahrenheit}$ with energy content of natural gas (BTU/Sales unit) is referred to calculate the amount of steam generated per MMCF of natural gas [73]
2. Total cost set up of plant is calculated in USD/KW and converted into USD/BTU to calculate the cost per lb. of steam from natural gas.
3. From step 1, amount of steam (lb.) generated is calculated from 1 BTU of energy.
4. To get the cost per lb. of steam generation by natural gas, divide step 2 by step 3

Chapter 6 ASSUMPTION

6.1 Steam from Solar Powered Generator

1. For the calculation of total amount of heat in BTU required to heat water at 70 deg. Fahrenheit into superheated steam at 450 degree Fahrenheit, small scale solar powered generator is assumed in operation. Additionally the rate of incoming water is assumed to be 10 gallons/min.
2. Only one heliostat is assumed which is 13.98 m² in area that strikes the sun rays onto the receiver for conversion of water into steam.
3. For heating the steam to 450 degree F, it is assumed that the quality of steam produced is 80%. The efficiency of this system is assumed to be 39% with 320 days of operation.
4. The total cost of investment, installation, operation and maintenance was found for a solar steam generation plant of 50KW. It is assumed that economy of scale will be constant all these cost in USD is calculated per KW.

6.2 Steam from Natural Gas Powered Generator

1. The efficiency of the process is assumed to be 85% as not all the natural gas from pipelines or tankers is used for the conversion of water into steam.

Chapter 7 CALCULATIONS

7.1 Steam from Solar Powered Generator

The steps below determine the heat required to raise 10 gallons of water from 70 degree Fahrenheit to the boiling point of 212 degree Fahrenheit:

STEP-1 Total weight of water = 10 gal x 8.3 lbs. / gal = 83 lbs.

Temperature change = $T_2 - T_1 = 212 - 70 = 142$ degree Fahrenheit.

H_w , the total heat required to heat the water = 1 BTU/lb – deg x 83 lb. x 142 deg = 11,786 BTU

Available solar power density is 1.0 kWh/hr./m², a solar collector can absorb 3412 BTU/hr./M².

Therefore, heat per hour: $H_h = 3,412 \frac{\text{BTU}}{\text{hr} \times \text{M}^2} \times 13.98 \text{ M}^2 = 47,699 \text{ BTU/hr.}$

Therefore, it will take T_h hours, where: $T_h = H_w / H_h = 11,786 \text{ BTU} \div 47,699 \text{ BTU/hr} = 0.24 \text{ hrs.}$

Total Heat per hour = 11,786 ÷ 0.24 hrs = 49,108 BTU/hr.

STEP-2 Heat of Vaporization for water = 970 BTU/lb. To vaporize 10 gal of water at 212 degree to steam, the following amount of heat is needed:

$H_v = 10 \text{ gal} \times 8.3 \text{ lb/gal} \times 970 \text{ BTU/lb} = 80,510 \text{ BTU}$

Available solar power density is 1.0 kWh/hr./m², a solar collector can absorb 3,412 BTU/hr./M².

Therefore, heat per hour: $H_h = 3,412 \frac{\text{BTU}}{\text{hr} \times \text{M}^2} \times 13.98 \text{ M}^2 = 47,699 \text{ BTU/hr.}$

The time required to make 83 lbs. of steam from 10 gals of water at the boiling point is:

$T_v = 80,510 \text{ BTU} \div 47,699 \text{ BTU/hr} = 1.68 \text{ hours}$

Total Heat per hour = 80,510 ÷ 1.68 = 47,922 BTU/hr.

STEP-3

83 lbs. of 80% steam is further heated to 450 degree F at 414.7 psia.

First plot the pressure on graph as P and steam quality on graph as Q. Draw a straight line through P and Q to get W1. W1= 25 watts/hr./lb.

Plot the degree of superheat on graph S. The degree of superheat equals operating temperature minus saturated temperature. S= 450-212= 238 degree F

Draw a straight line through P and S to get W2. W2= 120 watts/hr./lb.

Safety Factor is assumed to be 1.2

Required KW/hr = $83 \text{ lb.} \times \frac{(120-25)\text{watts}}{\text{hr} \times \text{lb}} \times \frac{1}{1000} \times 1.2 = 9.46 \text{ KW/hr}$

To convert kW to BTU simply multiplies by 3412.

Total heat per hour = 9.46 x 3412 = 32,284 BTU/hr.

Figure 7-1 Steam Superheat Nomograph [73]

Total heat required= 49,108 + 47,922 + 32,284 = 129,314 BTU/hr.

Therefore to calculate how much amount of steam was produced-

$$\frac{129,314 \text{ Btu}}{\text{hr}} \times \frac{\text{Lb}}{1206 \text{ Btu}} \times 0.39 = 41.81 \text{ lb of steam per hour of solar energy}$$

1206 Btu/lb is obtained from superheated steam table at 414.7 psia and 450 degree F. [73]

Assuming there are 6000 collectors each with a 13.98 m² area, total steam generated at an average of 8 hours per day directly from sun and rest 16 hours from storage unit for a year = $6000 \times 41.81 \times 24 \times 320 = 1,926,604,800$ lb.

The amount of steam generated per BTU = $41.81 \div 129,314$ or

$1,926,604,800 \div [(1,926,604,800 \times 129,314) \div 41.81] = 3.233 \times 10^{-4}$ lb./Btu

Average Cost = Total Cost/Total Steam, USD/LB [74]

Total Cost = Investment+ Installation + Operation and Maintenance

Total Cost= 25,749 USD/KW = $25,749 \div 3412 = 7.54$ USD/BTU

Average Cost per Lb. of steam= $7.54 \text{ USD/BTU} \div 3.233 \times 10^{-4} \text{ lb/BTU} = \underline{\underline{\$23,321/\text{Lb.}}}$

Investment Cost	
Labour Cost: Site and Solar Field	USD/KW
Solar Field	1248
Site Prep and Infrastructure	226
Steel Construction	424
Piping	128
Electric Installation and others	288
Equipment: Solar Field and HeatTransfer System	USD/KW
Mirror	462
Receiver	518
Steel Construction	780
Pylon	6
Foundation	156
Motors	32
Swivel Joint	52
HTS (pipipng, insulation, heat exchangers and pump)	390
Storage System	USD/KW
Storage Tanks	132
Insulation Material	14
Foundation	46
HeatExchangers	102
Pumps	32
Others	USD/KW
Project Development	210
Project Management	562
Financing	436
Other Cost (Allowance)	210
Total	6454

Installation Cost	USD/KW
Parabolic Trough	7100
Solar Tower	9000
Heat Transfer System	1068
Thermal Energy Storage	2020
Total	19188.398

O&M Cost	USD/KW
Onsite Staff	54
Utilities- Water	0.42
Consumables	9
Maintenance & Repairs	
Solar Field	10.16673
HTF System	3.152816
TES System	3.533233
Power Block	23.0058
Water Treatment	0.845592
Office & Administration	1.07034
Training	0.824515
Contract Services	0.382922
Miscellaneous Cost	1.160709
Total	107

Total Cost, USD/KW	25749	USD/KW
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Table 7-1 Total Cost of Steam Generation by Solar [75]

7.2 Steam from Natural Gas Powered Generator

To calculate the amount of steam from the required natural gas, following tables were referred to-

Fuel Type, sales unit	Energy Content, Btu/sales unit	Combustion Efficiency, %
Natural Gas, MMBtu	1,000,000	85.7
Natural Gas, thousand cubic feet	1,030,000	85.7

Table 7-2 Energy Content and Combustion Efficiency of Fuels [76]

Step 1 Referring the tables above, $1030 \times 10^6 \text{ Btu}$ of energy is produced per MMcf of natural gas and 943 Btu energy is required to produce 1 lb. of steam.

943 Btu/lb is obtained from superheated steam table at 1150 psia and 515 degree F [73]. The amount of steam generation per MMCF of natural gas is calculated as follows-

$$\frac{1030 \times 10^6 \text{ Btu}}{\text{MMcf}} \times \frac{\text{Lb}}{943 \text{ Btu}} \times 0.85 = 928,420 \text{ lb per MMcf of natural gas}$$

Step 2 Total Plant cost equals= 4495 \$/KW = 4495/3412 \$/BTU = \$1.32/Btu

Investment Cost	USD/KW
Civil/Structure	80
Mechanical Gas Turbine	584
SCR	60
Gas Compressor	128
Electrical	110
Piping	28
Instruments and Controls	18
Natural Gas	1075.2
Balance of Plant/General Facilities	68
Total	2151.2

Maintenance & Repairs	USD/KW
Water Treatment	0.845592
Office & Administration	1.07034
Training	0.824515
Contract Services	0.382922
Miscellaneous Cost	1.160709
Indirect Costs	56
Engineering and Home Office Costs	126
Project Contingency	188
Gas Turbine Cost	560
Total	934

Installation Cost	USD/KW
Gas Turbine Combined Cycle Plant	1410

Total	4495	USD/KW
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Table 7-3 Total Cost of Steam Generation by Natural Gas [75] [76]

Step 3 928,420 lb Steam is generated from $1030 \times 10^6 \text{ Btu}$ natural gas. Which means $9.01 \times 10^{-4} \text{ lb}$ of steam is generated from 1 Btu of natural gas.

Step 4 Therefore,

$$\frac{\$1.32}{\text{Btu}} \times \frac{\text{Btu}}{9.01 \times 10^{-4} \text{ lb}} = \frac{1,465\$}{\text{lb}} \text{ of steam generated from natural gas.}$$

To further calculate the NPV for the SSG and HRSG, nominal discount rate is assumed 10% with inflation rate of 4%. From nominal discount rate and inflation rate, real discount rate is calculated to be used in finding NPV. The NPV for both these cases are shown below.

Solar	
Year	Cash Flow
0	-10693
1	-22972
2	-21099
3	-19225
4	-17352
5	-15478
NPV	\$ (93,078.23)

Natural Gas	
Year	Cash Flow
0	-5960
1	-526
2	1348
3	3221
4	5095
5	6968
NPV	6804.38

Table 7-4 Cash Flow for SSG and HRSG

Chapter 8 RESULTS

For the 1st case of generation of steam by solar plant, the total cost of steam is calculated to be \$23,321 per lb. and the total cost of plant for this operation is \$25,749 per KW. For case 2nd of generation of steam by natural gas, total cost of steam is \$1,465 per lb. and total cost of plant for this operation is \$4,495 per KW. With time in different countries, the cost of natural gas changes. The calculation was specific to plant cost and upon increased price of natural gas, the cost difference of the production of steam decreases making solar steam generators more competitive.

The Summary of results is shown in the table below-

RESULTS	Steam Cost, USD/Lb	Total Plant Cost, USD/KW
Solar	\$23,321	\$25,749
Natural Gas	\$1,465	\$4,495

Table 8-1 Summary of Results

Figure 9-3 Yearly Solar Radiance[77]

Much of the heavy oil that is recovered is located in location with good solar resources. Comparing the figures above, the most suitable location for the setup of solar steam generator is California, Venezuela, Saudi Arabia, and Iraq. The graphs below show monthly mean minimum and maximum daily temperature and monthly total sun hours for suitable locations mentioned above.

California-

Figure 9-4 Average Minimum and Maximum Temperature in San Francisco, U.S.A

Figure 9-5 Average Monthly Sun hour in San Francisco, U.S.A [78]

Venezuela

Figure 9-6 Average Minimum and Maximum Temperature in Tumeremo, Venezuela

Figure 9-7 Average Monthly Sun hour in Tumeremo, Venezuela[79]

Saudi Arabia-

Figure 9-8 Average Minimum and Maximum Temperature in Riyadh, Saudi Arabia

Figure 9-9 Average Monthly Sun hour in Riyadh, Saudi Arabia[80]

Iraq-

Figure 9-10 Average Minimum and Maximum Temperature in Bagdad, Iraq

Figure 9-11 Average Monthly Sun hours in Bagdad, Iraq[81]

To find the most suitable locations for generation of steam by solar steam generators or hybrid generators, the table below compares heavy oil reserves to annual solar radiance and natural gas pricing.

Country	Annual Solar radiance	Heavy Oil Reserves	Natural Gas Price	
Russia	1400 Kwh/M ²	More than 1 trillion barrels in place.	Year	Natural Gas Spot Price Dollars per Million Btu [82]
			2016	5.16
			2015	5.81
			2014	10.45
			2013	10.99
			2012	11.64
Saudi Arabia	2500 Kwh/M ²	Up to 100 Billion barrels in place.	Average 2.16	
Iraq	2700 Kwh/M ²	Up to 100 Billion barrels in place.	Average 2.08	
Venezuela	2100 Kwh/M ²	More than 1 trillion barrels in place.	Average 1.89	

Canada	1700 Kwh/M ²	More than 1 trillion barrels in place.	Year	Natural Gas Spot Price Dollars per Million Btu [83]
			2016	2.05
			2015	2.64
			2014	4.23
			2013	3.03
			2012	2.31
U.S.A	2100 Kwh/M ²	Up to 100 Billion barrels in place.	Year	Natural Gas Spot Price Dollars per Million Btu [84]
			2016	2.52
			2015	2.62
			2014	4.37
			2013	3.73
			2012	2.75

9.2 Advantages of Solar Enhanced Oil Recovery

9.2.1 Financial

1. Operators of Solar Enhanced Oil Recovery can hedge against the fuel price volatility as solar energy is free and this could further improve the economics of oil production [85].
2. With the use of this technology, the value of natural gas is maximized. As may oil producing countries use natural gas for the EOR operation, this puts them in direct competition with industrial development. With the use of solar EOR, there will be more natural gas availability for other industry boosting the economic activity. Additionally, solar EOR reduces the gas usage by 80% [86].
3. Once installed, solar generators can produce steam for 30 years with 60% reduced operating cost [85].

8.2.2 Technical

1. Solar power towers are simple and easy to operate compared to gas steam generators [87].

2. More oil can be economically recovered compared to gas steam generators with optimized solar steam strategy of heliostat design coupled with advanced aiming controls and software [88].

9.2.3 Social and environmental impact

1. Solar EOR reduces nitrogen oxides and carbon emission enabling producers to expand production without being concerned about the increasing regulations and constraints from carbon legislature [89].

In future if the companies are charged for every ton of carbon emission, with the use of this technology, companies will spend a lot lesser. This technology has a positive impact on the environment.

2. Development of solar fields and wells will create more job opportunities leading to powerful economic stimulus [90].

9.3 Disadvantages of Solar Enhanced Oil Recovery

9.3.1 Financial

1. The initial installing cost and capital cost of solar power steam generator is very high compared to the gas steam generators. Additionally, it could take up to 10 to 15 years to break even with the initial investment cost [91].

9.3.2 Technical

1. Location of heliostat is dependent on the availability of sunlight. This plant can only be setup where the availability of sunlight is high. Areas where it remains cloudy or foggy, installing solar EOR plant is not suitable. Additionally, at night as solar energy cannot be obtained, the plant has to generate steam by natural gas [92].

2. Although there are solar storage systems attached to solar power towers, the reliability of this system is very low during the night time or less sunny days [87].

3. Most of the solar panels have only 40% efficiency as 60% of the sunlight that strikes gets wasted. Most of the upcoming technologies are focused on harnessing the wasted energy to make the system more efficient. With the increased efficiency, the price of the heliostats has gone higher [93].

4. The area needed for the installation is huge averaging of up to 9.5 sq mi (25 km²). Additionally, once solar field is laid it cannot be moved [94].

9.3.3 Social and environmental impact

1. The wind condition can have a severe impact on heliostat as the operating limit is up to 25 mph wind. Anything above it can reduce the efficiency of heliostat [95].
2. For the dust, additional use of water is used by enclosed cleaning trough [96].

9.4 Advantages of Natural Gas Enhanced Oil Recovery

9.4.1 Financial

1. The production of steam by natural gas is very cheap compared to the solar production of steam as the installation cost is significantly less. Additionally, the technological advancement in shale has made natural gas easy to recover in large quantity, making it cheaper [97].

9.4.2 Technical

1. Natural gas is easy to be stored in salt formations and aquifer reservoirs or transported by tankers and pipelines. This makes it more reliable to produce steam in different weather conditions during day and night [98].
2. Less space is required compared to solar EOR for the setup of Heat Recovery Steam Generators [97].
3. The efficiency of natural gas steam generators is very high of up to 85% [99].

9.4.3 Social and environmental impact

1. Compared to fossil fuel such as coal, natural gas produces 50% less carbon emission [100].
2. In the U.S, as technological advancement has unlocked enough natural gas jobs. This industry supports more than 2.8 million jobs in the U.S [101].

9.5 Disadvantages of Natural Gas Enhanced Oil Recovery

9.5.1 Financial

1. Operators of Natural Gas Enhanced Oil Recovery cannot hedge against the fuel price volatility as natural gas is not free and this could affect the economics of oil production [102]. The operating cost is higher in the Steam production by natural gas compared to steam produced by solar power.

9.5.2 Technical

1. As natural gas is odorless, the leaks can go undetected further causing explosion. This can be extremely toxic when inhaled. Production of methane is 21 times more dangerous than carbon dioxide.
2. For using the natural gas to further produce steam, processing is needed which further produces sulfur, water vapor, carbon dioxide, and even helium and nitrogen.

9.5.3 Social and environmental impact

1. Natural gas is nonrenewable source of energy and cannot be considered long term supply solution as compared to solar energy [103].
2. Although natural gas emits 50% less carbon dioxide than other fossil fuels, it considerably has more carbon emissions when compared to solar energy.
3. Natural gas is a source of terrorism and violence. Gas investigation happens in nations with the most noticeably bad records of fascism, for example, the Middle East, and African nations. The income from characteristic gas deal discovers route into pockets of these despots who gather trillions of dollars. This marvel drives up savagery as oil and gas cash wind up in the hands of terrorists [98].

Chapter 10 CONCLUSION

With the drop in the prices of oil, investments in technology have significantly dropped. However, investment in innovation is needed as less investment today means less of future supply. With low investment cost, the future exploration and recovery cost of oil will not drop and would bring companies back to the beginning of the cycle [104]. This project focuses on highlighting an appropriate technology, solar wells, that oil industry can consider for investment. Solar steam generators operate from the solar power and compared to HRSG, have low ongoing operation and maintenance cost. Solar generators can be upgraded as per the company's demand and are modular. If more steam is to be generated, more heliostats are added. They also have 3 important components, which are comparatively fewer than HRSG and requires low maintenance including quick wash in a year or two. Further, in order to pursue companies to invest in the solar steam generators for the recovery of heavy oil, it is compared to the steam generators run by natural gas. In order to compare these two generator systems, the goal is to find the cost of steam production by both these methods to support the comparison. The investment cost in solar steam generator is almost 3 times higher than that natural gas generator however, operation and maintenance cost of natural gas is approximately 9 times higher than that of solar generators. As both these plants have their own pros and cons, a combination of these two system can be considered. The hybrid system can bring down the cost of solar steam generation making it environmental friendly. When the prices of natural gas increase, the price difference for the setup of combination system vs HRSG will not be much apart. Hence, the recommendations are made to big oil companies to invest on a combined systems and with time and increased cash flow, expand into SSG setup. The NPV calculation shows that the solar investment have a negative return up until 14 years and natural gas generators gets their positive return starting 2nd year. Based on this result, HRSG are profitable but SSG are environmental friendly. Comparing the countries above from the discussion chapter, best possible locations for the setup of hybrid plant are Saudi Arabia, Iraq, Venezuela, and U.S.A as they have high Annual Solar radiance with high heavy oil resources and low natural gas prices.

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