Approaches for Integrating Renewable Energy Technologies in Oil and Gas Operations

Sean Ericson, Jill Engel-Cox, and Doug Arent

The Joint Institute for Strategic Energy Analysis is operated by the Alliance for Sustainable Energy, LLC, on behalf of the U.S. Department of Energy's National Renewable Energy Laboratory, the University of Colorado-Boulder, the Colorado School of Mines, the Colorado State University, the Massachusetts Institute of Technology, and Stanford University.

Technical Report
NREL/TP-6A50-72842
January 2019

Contract No. DE-AC36-08GO28308

Approaches for Integrating Renewable Energy Technologies in Oil and Gas Operations

Sean Ericson, Jill Engel-Cox, and Doug Arent

The Joint Institute for Strategic Energy Analysis is operated by the Alliance for Sustainable Energy, LLC, on behalf of the U.S. Department of Energy's National Renewable Energy Laboratory, the University of Colorado-Boulder, the Colorado School of Mines, the Colorado State University, the Massachusetts Institute of Technology, and Stanford University.

The Joint Institute for Strategic Energy Analysis
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.jisea.org

Technical Report
NREL/TP-6A50-72842
January 2019

Contract No. DE-AC36-08GO28308

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos: (left to right) NREL 04135, iStock 22779761, NREL 16933., NREL 15648, NREL 08466, NREL 21205

NREL prints on paper that contains recycled content.

Acknowledgments

The authors wish to acknowledge preliminary work on this paper completed by Harshit Jayaswal and Andrew Larson, both former interns with the Joint Institute for Strategic Energy Analysis (JISEA) at the National Renewable Energy Laboratory (NREL). Special thanks also go to the attendees at the International Energy Agency (IEA) Gas & Oil Technology (GOT) Collaboration Programme event on "Nexus of Oil & Gas and Renewables in the Energy Future" conducted at NREL on September 27–28, 2017, for their inspiring presentations and discussion.

List of Acronyms

CDU	crude distillation unit
CSP	concentrated solar power
EOR	enhanced oil recovery
ESP	electric submersible pump
FCC	fluid catalytic cracker
GOT	Gas & Oil Technology
GW	gigawatt
IEA	International Energy Agency
ITC	investment tax credit
JISEA	Joint Institute for Strategic Energy Analysis
MW	megawatt
NER	net energy ratio
NREL	National Renewable Energy Laboratory
psi	pounds per square inch
PV	photovoltaics
VDU	vacuum distillation unit

Executive Summary

Petroleum (including both oil and gas) heats our homes, drives our transportation system, generates electricity, and makes modern life possible. Continued demand from developed countries along with growth from developing economies implies demand for oil and gas will likely continue to be robust. Considering the desire to maximize production efficiency and economic returns, there is increased attention to the fact that nearly 10% of oil is consumed in the process of oil production, transportation, and refining (Halabi, Al-Qattan, and Al-Otaibi 2015) and that a quarter of a barrel of oil is used to produce a barrel of heavy oil (Wesoff 2015). As oil and gas development shifts to secondary and other non-conventional sources, meeting future demand is anticipated to require substantial amounts of energy to produce, transport, and refine petroleum.

Increasing efficiency of operations can mitigate the rising costs associated with increasing energy requirements. So can incorporating alternative energy sources that maximize product revenue while simultaneously addressing local environmental concerns as well as meeting emissions goals. This second factor has prompted a growing interest in integrating renewable energy technologies in oil and gas operations. Furthermore, due to dramatic declines in the cost of energy generated from renewable sources, integrating renewable energy technologies can, in many cases, reduce operations costs as well. This report provides an overview of where renewable energy technologies can economically be integrated into oil and gas operations. The following are key findings from the study.

1. **The role of renewable energy generation in oil and gas operations could greatly increase.** The trends of increasing energy intensity in oil and gas extraction, growing concern over emissions, and declining renewable generation costs are leading to a growth in applications where renewable technologies can cost-effectively be integrated into oil and gas operations.
2. **Several barriers must be overcome to effectively integrate renewable generation technologies.** Renewable technologies must be cost competitive and meet operational requirements. Oil and gas industry staff must be trained in any operational differences between the use of onsite renewable energy generation versus other energy sources with which they may be more familiar to enable uptake at the operations level.
3. **Countries seeking fossil fuel energy subsidy reform may present opportunities for renewable integration.** Several countries with fossil fuel energy subsidies are attempting to reduce or eliminate the subsidy programs to reduce fiscal spending and promote efficiency. Renewable technologies can present a means of lowering costs by improving operation efficiencies, thereby dampening cost shocks from subsidy reform.
4. **Enhanced oil recovery (EOR) applications present near-term opportunities for renewable integration in upstream production.** Water and steam injection for secondary and tertiary EOR, respectively, are well-suited applications for integration with renewable generation. The rate and timing of energy production required to create the steam and inject either the steam or the water do not impact the effectiveness of these processes, meaning project economics are not significantly impacted by the variability of renewable generation (Sandler, Fowler, et al. 2012). Concentrated solar power to produce

steam for EOR is already seeing commercial applications, and offshore wind power for water injection may be in commercial applications in the near future.

5. **Electrification of drill rigs and other upstream equipment can reduce emissions, noise, and costs and can be powered through connection to the grid or mini-grids with renewable power.** Drilling operations and production equipment primarily rely on diesel generators to meet power needs. Diesel fuel can be expensive and controlling generator noise and emissions can be difficult. The ability to reduce noise and emissions is especially important for operations close to population centers, where noise and emissions regulations are often more stringent. Grid electricity, along with onsite renewable generation sources, can reduce operations costs and decrease associated emissions and noise pollution.
6. **The utilization of renewable powered electric motors to power natural gas compressor stations can be an effective means to increase renewable integration in midstream transportation.** Electric motors powered by the grid generally have lower net emissions and have more operational flexibility than gas engines or turbines (Greenblatt 2015). Hence, electric motors can provide both economic and environmental benefits.
7. **Refineries offer multiple opportunities for renewable integration, but their high energy intensity, including high thermal demands, may require new solutions.** Oil refining is the most energy-intensive part of the supply chain. Petroleum refining is the largest consumer of fuel in U.S. manufacturing and is the largest generator of onsite greenhouse gas emissions in the manufacturing sector (Halabi, Al-Qattan and Al-Otaibi 2015; Brueske, Sabouni and Zach 2012; EPA 2018). In locations with sufficient sunlight and available land, solar generated heat can be integrated into the refining process. Renewable generation can also be used to produce hydrogen, which is an important input in oil refining. Finally, electricity and heat cogeneration can be integrated into the refining process to reduce energy intensity and emissions.

Putting these findings together, it is possible to envision oil and gas production that leverages clean power to decrease costs and maximize production while reducing environmental impacts. Adapting low-cost renewable energy technologies to oil and gas production, as well as to other extractive and industrial processes, enables conservation of energy-dense liquid fuels and versatile natural gas for high value uses, such as petrochemicals and aviation, while expanding profitability and increasing sustainability for both energy sectors.

Table of Contents

List of Figures

1 Introduction

Petroleum (including both oil and gas) heats our homes, drives our transportation system, generates our electricity, and makes modern life possible. Continued demand from developed countries along with growth from developing economies implies demand for oil and gas will likely continue to increase (International Energy Agency 2017). Under current policies, global oil demand in 2040 is expected to be roughly 26 million barrels per day greater than in 2016 (International Energy Agency 2017).[1]

As demand is increasing, conventional oil and gas reserves are decreasing, leading to a shift in production to unconventional sources and a growing use of enhanced oil recovery (EOR) techniques. Production from unconventional reserves and the use of EOR raises the energy intensity of an already energy intensive industry. Nearly 10% of oil is used in the production, transportation, and refining process (Halabi, Al-Qattan and Al-Otaibi 2015). This number is even higher for many unconventional sources—it takes a quarter of a barrel of oil to produce a barrel of heavy oil (Wesoff 2015). Energy used to produce, transport, and refine oil represents major operations costs. Furthermore, many oil and gas companies have set goals or made corporate level commitments to reduce their greenhouse gas emissions, in part to address issues raised by in national and global studies (USGCRP 2017), (IPCC 2018). The petroleum industry faces the difficult task of meeting growing demand and growing operational energy needs while reducing operations emissions.

One way to meet growing energy demand and production energy intensity, while also meeting emissions targets, is to integrate renewable generation technologies into oil and gas operations. Incorporating renewable energy technologies and otherwise reducing the amount of fossil fuels used to produce, transport, and refine petroleum can decrease both energy costs and emissions, as well as preserve oil and gas resources for their highest value uses.

The oil and gas industry has several aspects that are conducive to integrating renewable energy technologies. Production facilities are often both in remote locations and require large amounts of electricity that could be generated with renewable sources (wind, solar). EOR and oil refining also require large amounts of heat, which may be supplied by renewable thermal technologies (solar thermal, geothermal). Use of waste heat or gas to run cogeneration facilities can, in some cases, also be economic.

Renewable energy technologies are already integrated in some oil and gas operations. Furthermore, the combination of increasing energy intensity in the petroleum industry and dramatic decreases in costs for many renewable energy technologies is shifting the economic calculus in favor of more integration. However, renewable energy technologies are not applicable in all cases. Renewable energy technologies must be both reliable and economically competitive to be commercially viable.

This paper provides an overview of where renewable energy technologies can be integrated into oil and gas operations. The rest of this paper is divided into seven sections. The first section

[1] This represents a 27% increase from the average demand in 2016 of 96.2 million barrels per day.

discusses trends that are leading to an increase of renewable technology integration in oil and gas operations. The second section provides an overview of key challenges to renewable integration and discusses factors that determine if a given technology can be reliably and affordably integrated. The third section discusses relevant government policies and social considerations that influence the relative benefits of renewable integration. Sections four, five and six discuss opportunities for renewable technologies to be integrated into upstream production, midstream transportation, and downstream refining processes, respectively. The final section summarizes key findings and concludes.

2 Current Trends and Growing Opportunities

Three parallel trends are increasing the profitability of renewable technology integration in oil and gas operations. The trends are:

1. Depletion of higher-quality oil reserves leading to an increased energy intensity of petroleum operations
2. Environmental leadership in the oil and gas industry
3. Falling costs for renewable generation technologies.

This section analyses each trend and discusses the implications for renewable integration.

2.1 Depletion of High-Quality Oil Reserves

In the early days of the petroleum industry, shallow oil and gas reserves with ample reservoir pressure were in abundant supply. Today, easy-to-reach oil and gas resources are largely depleted. Remaining reserves are marked by deeper reservoirs, lower pressures, and lower quality. As an example, Figure 1 displays the increase in average water and well depths in the Gulf of Mexico. Deeper water and deeper wells increase both the complexity and the energy intensity of operations. The trend toward production from lower-quality reserves may also be seen in terms of the increased exploitation of heavy oil and tar sands and the increased use of EOR techniques—the injection of gas, heat, or liquid to increase field recovery rate.

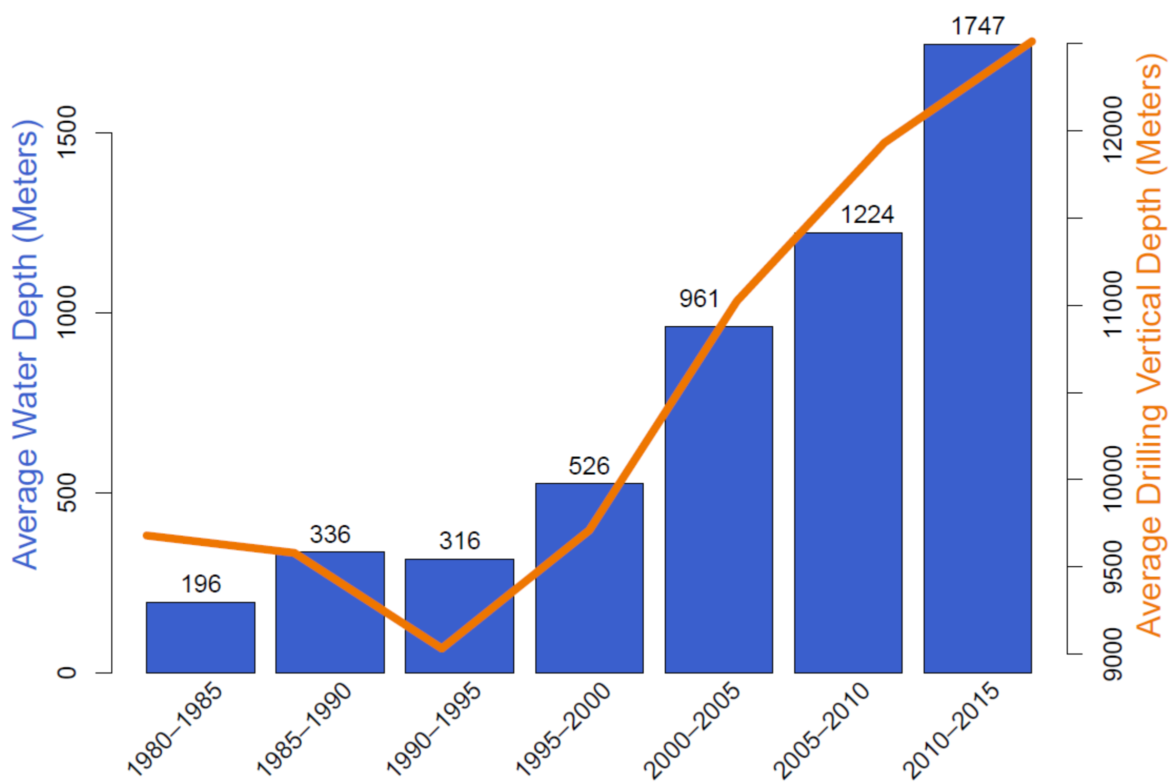

Figure 1. Average water and drilling depth in the Gulf of Mexico over time. *Data from* (BOEM 2017)

While sufficient petroleum resources remain to meet demand for the foreseeable future, the shift toward marginal reserves increases the energy intensity of production. A 2017 study of five large petroleum fields concludes that the net energy ratio (NER)—the ratio of energy produced to the energy used to produce it—for each field declined by 46% to 88% over the last four decades (Tripathi and Brandt 2017). An in-depth analysis of conventional natural gas production in Canada shows a similar trend, with the ratio of energy output to energy input falling by roughly half from 1993 to 2009 (Freise 2011). A combination of declining field production and increased energy expenditures on enhanced recovery methods contributed to the decline in NER (Tripathi and Brandt 2017).

Lower-quality reserves lead to higher energy intensity in production, transportation, and refining of petroleum. This leads to more demand for energy in each stage of the petroleum supply chain, which in turn leads to more possibilities for renewable technology integration to reduce energy costs. Along with cost savings, renewable technologies can reduce emissions, which is becoming an increasingly important factor.

2.2 Environmental Leadership in the Oil and Gas Industry

Industrial oil and gas practices have continued to advance to meet or exceed environmental regulations. Adverse incidents are rare but sometimes of high consequence. It is well recognized that oil and gas operations emit pollutants, and continuous or episodic activities or incidents may lead to environmental degradation. Improperly drilled or completed wells can lead to oil spills, contaminated water spills, and methane leaks. Machinery such as compressors and diesel generators increase noise and air pollution. Operations can lead to traffic congestion, and drilling processes can contaminate water supplies. Finally, petroleum refining processes emit gases including carbon dioxide, carbon monoxide, methane, organic compounds, nitrogen oxides, sulfur dioxide, and hydrogen sulfide. Meeting environmental regulations can be costly, and a failure to meet requirements may lead to fines and impact a firm's social license to operate.

Operations occurring in closer proximity to urban centers and suburban developments, as well as a growing awareness of the environmental effects of operations—both local effects such as air pollution and induced seismicity and global effects such as climate change—are further increasing the importance of environmentally sound production practices.

The petroleum industry already recognizes this fact and has been taking a leading role in reducing the environmental impact of operations. Due to industry action, greenhouse gas emissions from the major private oil companies fell by 13% between 2010 and 2015 (Hirtenstein 2017) and methane emissions from natural gas wells fell by 40% between 1999 and 2012 (Bluestein, et al. 2015). Furthermore, many oil companies have set goals for additional emissions reductions. Because of the falling costs, renewable energy technologies could become important tools for the goals of meeting additional energy demands and stricter emission standards while reducing fuel usage and operations costs.

2.3 Falling Renewable Energy Costs

Price declines in the last decade have revolutionized the economics of renewable energy technologies. In 2009, the average levelized cost of electricity from solar photovoltaics (PV) was more than seven times the cost in 2017. Figure 2 displays the steep cost decline of electricity produced from wind and solar. Whereas power from wind and solar used to be prohibitively expensive, they are now in some cases the lowest cost source of electricity. If expected continued future cost declines for electricity from wind and solar are realized, generation from these sources will become even more competitive in the coming years. Furthermore, battery storage technology and technology for demand-side management, which can compensate for generation variability, have also seen remarkable cost declines.

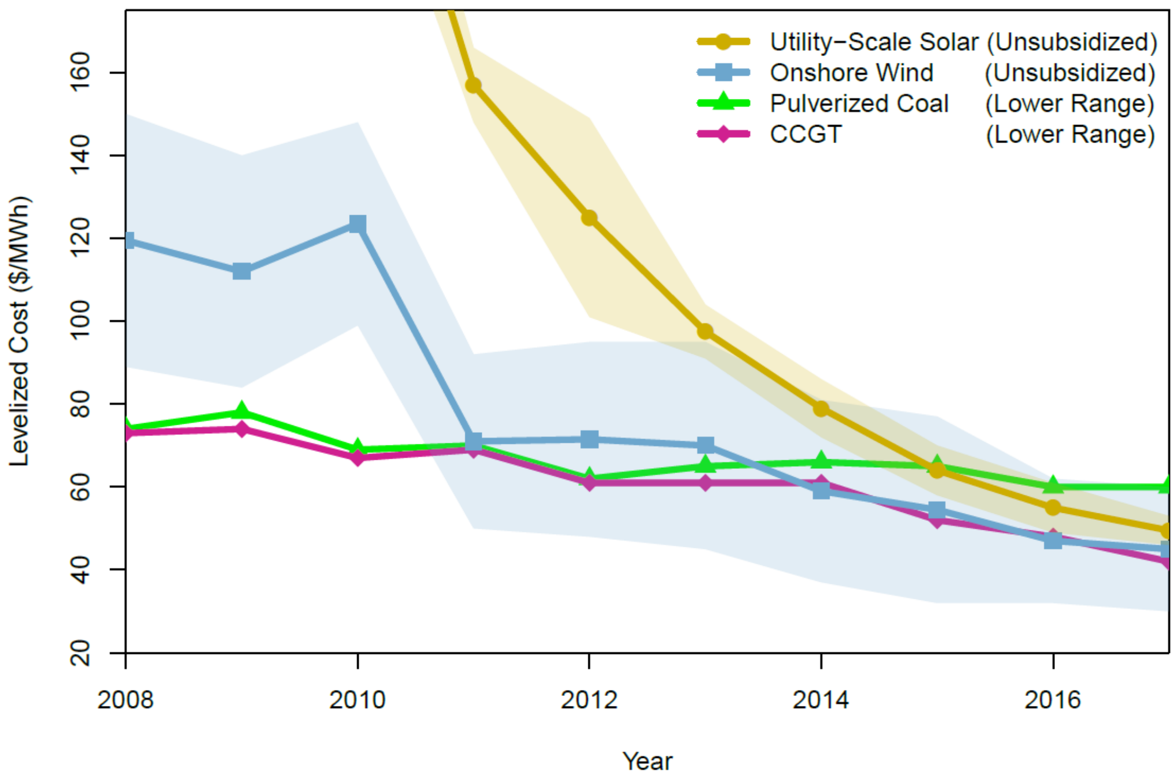

Figure 2. Levelized cost of various utility-scale generation technologies. ***Data from Lazard Levelized Costs of Energy reports from 2008–2017***[2]

The result of renewable energy cost declines is a paradigm shift in how renewable technology integration in oil and gas operations can be viewed. Whereas 10 years ago renewable technology was only applicable to cases where diesel or gas turbines could not be readily deployed, going forward renewable technology will, in a growing number of cases, be the lowest-cost solution. An understanding of where renewable generation is applicable and may be integrated can lead to both lower environmental impact and lower operation costs.

The following section discusses challenges to integrating renewable energy technologies into oil and gas operations. A solid understanding of these challenges helps make clear where renewable technologies are and are not applicable and where further development can help overcome these challenges.

---

[2] Bands for wind and solar represent low and high cost estimates. Because high cost estimates for coal and natural gas incorporate the cost of carbon sequestration, the figure uses low cost estimates instead of midpoint estimates for these technologies to better capture current production costs. Cost assumptions can be found in (Lazard 2017).

3 Challenges to Renewable Integration

Oil and gas operations are highly intricate, requiring coordination among multiple contractors, operators, and government agencies. Operations are capital intensive and require machines that operate reliably. The industry is also very competitive, with constant pressure to reduce costs. For renewable technologies to integrate into oil and gas operations, they must meet strict reliability and affordability metrics.

Cost has historically been the primary factor deterring renewable integration and is still the most important factor in determining whether a new technology can be integrated. However, even in cases where renewable generation is the lowest-cost solution, production variability and reliability concerns are still significant barriers to overcome. Operational considerations and differences in industry knowledge between oil and gas operations and renewable energy operations place an additional barrier to integration.

3.1 Variability of Generation

The effect of variability on operations is a large determinant of whether renewable technology can be integrated. Many operations along the supply chain require continuous power. Oil rigs, pipeline compressors, and petroleum refineries operate 24/7, regardless of whether the sun is shining or the wind is blowing. In these cases, renewable generation technologies can sometimes offer operational savings by being configured into a high reliability hybrid system with backup diesel generators, gas turbines, or battery storage. However, this potentially increases system costs and complexity. In other cases, such as steam injection for EOR, variability of generation has little effect on production since steam can be produced and then stored (Sandler, Fowler, et al. 2014). Use cases where variability in generation does not affect production have the highest potential for renewable integration.

While use cases where variability does not affect production are ideal, there are several methods for mitigating the effects of variability. In some cases, fuel savings alone can make renewable generation viable. High diesel costs and low efficiencies of natural gas reciprocating engines and single cycle turbines can lead to renewable integration being cost effective even when backup generation capacity is required (Korpas, et al. 2012). Battery storage technologies can also provide a solution in some cases. Many oil field operations, such as powering well sensors and lights and cathodic protection of pipelines from corrosion, employ solar power combined with battery storage (Halabi, Al-Qattan and Al-Otaibi 2015).

3.2 System Reliability

The petroleum industry requires high levels of reliability. Gas pipelines, for example, have much higher reliability of operations than the electricity grid, which itself has a high standard of performance (Greenblatt 2015; Liss and Rowley 2018). While renewable generation is well proven and shown to be reliable in a wide range of settings, systems for integrating renewable energy technologies into oil and gas operations often do not have an equally proven track record. Furthermore, reliability concerns are compounded by renewable generation variability. Systems may have to be designed to operate under a wide range of weather scenarios. Higher tolerance for extreme operating conditions and high reliability requirements (as well as space or weight constraints in some instances) raise costs, implying a renewable-generation-based system may be uneconomic even if it can provide energy at the lowest cost on average. More research and pilot projects can bridge this gap in understanding and substantiate that renewable systems can meet reliability standards.

3.3 Operational Considerations

Oil and gas operations are often subject to harsh conditions. Machinery must be able to withstand weather and temperature extremes and must be able to operate for several years before replacement. For a technology to be scalable, it must be able to operate under a variety of settings. Technologies that are robust and operate in a variety of settings are therefore most easily integrated.

Petroleum operations are very complex. Systems that add additional complications may be unsuited for practical applications even if they offer cost savings. Turnkey solutions that do not add to operational complexities can be most readily integrated. The ideal technology for integration in oil and gas operations is a system that can be installed easily and can operate cost-effectively with little to no maintenance.

Lastly, petroleum engineering is highly specialized and often requires a different skillset than that required for operations of renewable generation technologies. Along with research to ensure reliability, work is required to bridge the gap in industry knowledge between the petroleum and renewable energy industries, such as ensuring that gas and oil operations personnel are trained in operational aspects of renewable technologies as applied to gas and oil operations .

4 Government Policies

Private oil companies have an obligation to generate returns for their shareholders, and national oil companies have an obligation to generate revenue for their country. Thus, renewable integration must pass a test for cost effectiveness. However, the operating regulator and fiscal environment (e.g., tax codes), along with government policies and social environment, can have direct impacts on profitability. Policies such as emission regulations can greatly enhance the value of renewable technology integration, while policies such as fuel subsidies diminish their applicability. This section provides a brief overview of major policy considerations, which may affect the value of renewable integration.

Almost every country has implemented policies supporting renewable generation technologies. All but 11 countries have renewable energy targets, and most countries have renewable investment and or renewable production tax credits along with public investment or loans to support renewable energy (REN21 2017). The United States, for example, has a 30% federal investment tax credit (ITC) for qualifying renewable generation technologies and a production tax credit for many renewable generation technologies that do not receive the ITC. Several state and local policies further support renewable generation. Combined, these policies significantly increase the economics of renewable generation projects.

As renewable energy costs have fallen to the point where renewable prices are now in many cases competitive with other generation technologies, production and ITCs have been steadily phased out in many cases. Further phaseouts are planned and expected in the coming years. However, while tax credits will likely be lower in the future, the economics of zero-emissions generation may become more compelling in the coming years if carbon emission pricing and emission-reduction regulations are further adopted.

While renewable subsidies and emissions prices raise the value of renewable integration, some policies reduce the relative value of renewable technologies. The most notable of such policies are subsidies on electricity, oil, or natural gas. This is important as many of the largest oil-producing countries also have the largest fossil fuel subsidies. Figure 3 displays countries with the highest per capita fossil fuel and electricity subsidies. There is a clear correlation between petroleum-producing countries and countries with high levels of such subsidies.

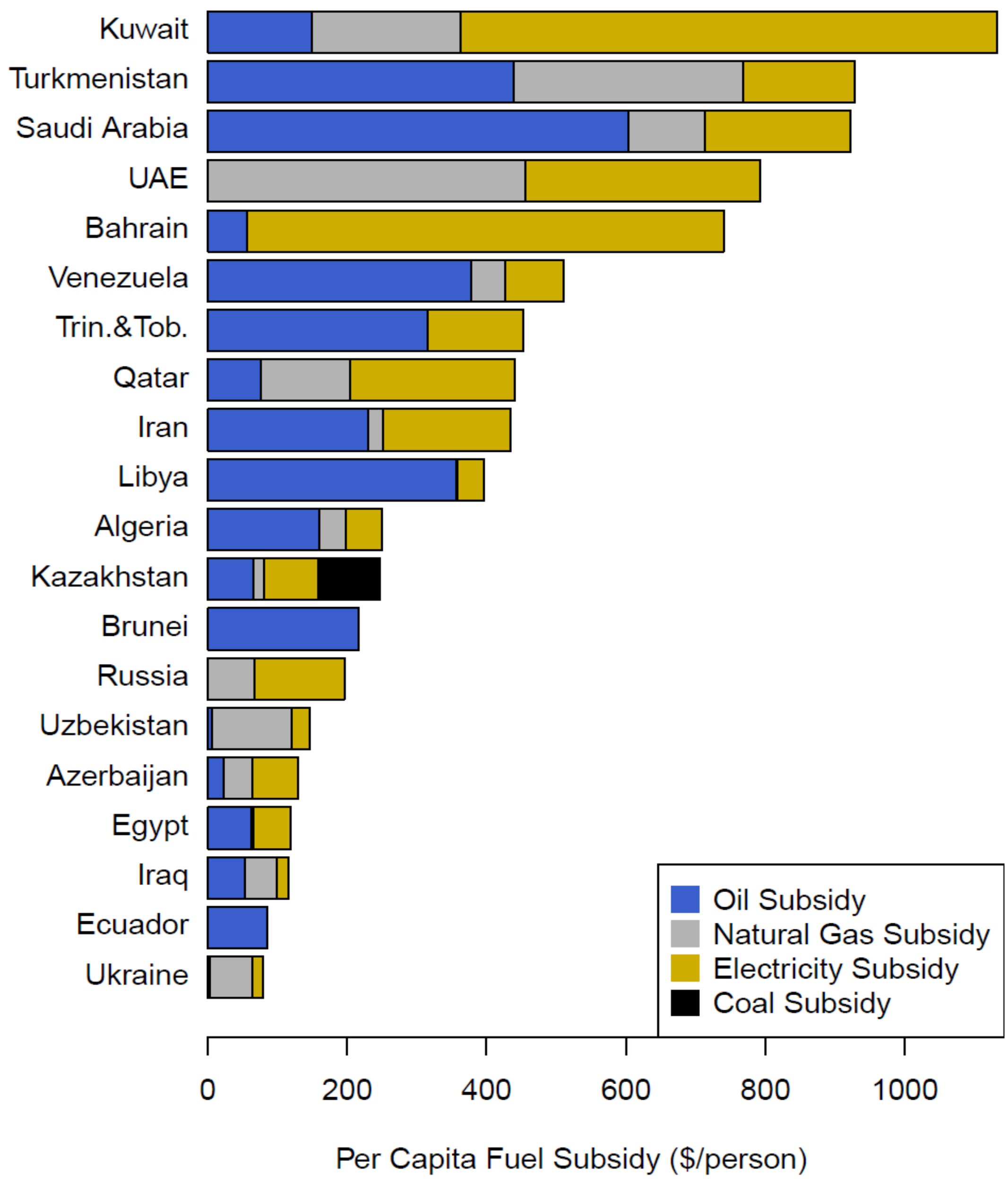

Figure 3. Total energy subsidy by country, 2016. ***Figure adapted from*** **(International Energy Agency 2017)**

Energy subsidies for traditional fossil fuels reduce the costs of producing heat and electricity for oil and gas operations, but they can also offer opportunities for renewable technologies (El-Katiri and Fattouh 2017). Fiscal costs of energy subsidies are leading to pressures for subsidy reform (Fattouh and El-Katiri 2012). Energy subsidies generally reduce investment in operation technologies, meaning operations in countries with energy subsidies are often inefficient (Fattouh and El-Katiri 2012; Sovacool 2017). Renewable integration in countries attempting subsidy reform presents an opportunity to increase operational efficiency and lower costs, thereby enabling subsidy reform: subsidy reform can be politically costly and can dramatically raise production costs. The Iranian subsidy reform in 2010 raised natural gas prices by over

700% and diesel prices tenfold (Fattouh and El-Katiri 2012). Renewable technologies can help dampen cost shocks from subsidy reforms. Thus, while energy subsidies diminish the opportunities for renewable integration, they present opportunities for countries attempting subsidy reform.

The three trends of declining reserve quality (and the resulting increase in energy requirements), growing environmental awareness, and falling renewable generation costs are leading to an uptake of renewable technologies along the supply chain. Government and industry policies are further helping to overcome integration challenges. In the following sections we cover applications for renewable integration in upstream, midstream, and downstream oil and gas operations. For each section of the supply chain, we discuss current commercial projects along with technologies that could soon reach commercialization.

5 Upstream: Renewable Integration in Oil and Gas Production

The oil and gas industry has a long history of integrating renewable energy in operations. One of the earliest commercial applications of solar PV panels was their use in warning lights for offshore oil installations starting in the early 1970s (Halabi, Al-Qattan and Al-Otaibi 2015). Often remotely located and off-grid, oil and gas operations primarily generate power by gas turbines or diesel generators, which can be expensive to operate and maintain. As production operations can have significant electricity requirements, power generation can be a substantial cost. For example, typical power requirements for an offshore platform are between 20 and 35 megawatts (MW) (Korpas, et al. 2012).

Renewable energy can be used to reduce fuel use and maintenance costs in upstream operations. Furthermore, renewable generation can reduce noise, reduce emissions, and increase safety. For each stage in the life of an oil field, different renewable technologies can be deployed. The three production stages are:

1. **Primary Recovery.** During primary recovery, there is sufficient well pressure for oil and gas extraction. Artificial lift methods such as electric submersible pumps (ESPs) and rod pumps are often used to increase output. About 5%–15% of reserves are extracted during primary recovery (Abromova, et al. 2014).
2. **Secondary Recovery.** As well pressures fall, production moves into the secondary recovery phase. Injection fluids or gas are used to increase reservoir pressure. An additional 10%–20% of reserves can be extracted from secondary recovery (Veld and Phillips 2010).
3. **Tertiary Recovery.** Also known as EOR, tertiary recovery consists of a variety of methods to stimulate production. Examples include: hydraulic fracturing, steam injection, in-situ combustion, and chemical injection. An additional 20% of total initial reserves may be extracted during tertiary recovery.

An individual field may not experience all three production regimes, and separate wells within a field may be in different regimes at any given period. However, the separation is a useful construct for both understanding general production stages and understanding where renewable generation technologies may be integrated.

Energy requirements vary throughout the life of the field. Operations energy intensity tend to be low during the primary recovery phase and then increase as well pressure declines. Hence, older fields, in the secondary and tertiary recovery phase, tend to have higher energy requirements than fields in the primary production phase. However, all phases in the production life cycle, along with drilling operations, offer opportunities for renewable technologies to lower costs and emissions.

5.1 Electrification of Drilling and Primary Recovery

Drilling entails significant short-term energy requirements. A single drilling rig can require more than 1 MW of power to operate (Quinlan, et al. 2011). As drilling operations only last a few weeks, these high-power requirements are only needed for a relatively short duration. Primary recovery operations, on the other hand, have relatively lower energy requirements that are sustained over several years.

The energy for drilling and primary recovery operations are often provided by diesel or natural gas generators. Diesel fuel requirements for drilling and constructing a conventional oil well typically range between 18,000 and 24,000 gallons (Clark, et al. 2011). For shale gas wells, fuel consumption is generally much higher, often requiring more than 50,000 gallons of diesel fuel per well and requiring more than 80,000 gallons in some plays (Clark, et al. 2011). Renewable generation can reduce or eliminate the need for a generator, which can result in substantial fuel savings.

When operations are sufficiently close to electrical lines, the electricity grid can be used to power operations. Using electricity can reduce noise, emissions, and traffic congestion, which can be especially important when operations are close to urban centers. An electrical connection also allows for renewable energy to be integrated into various points of operations via a microgrid. Microgrid solutions empower users to integrate distributed generation into a versatile, reliable, and environmentally friendly operation.

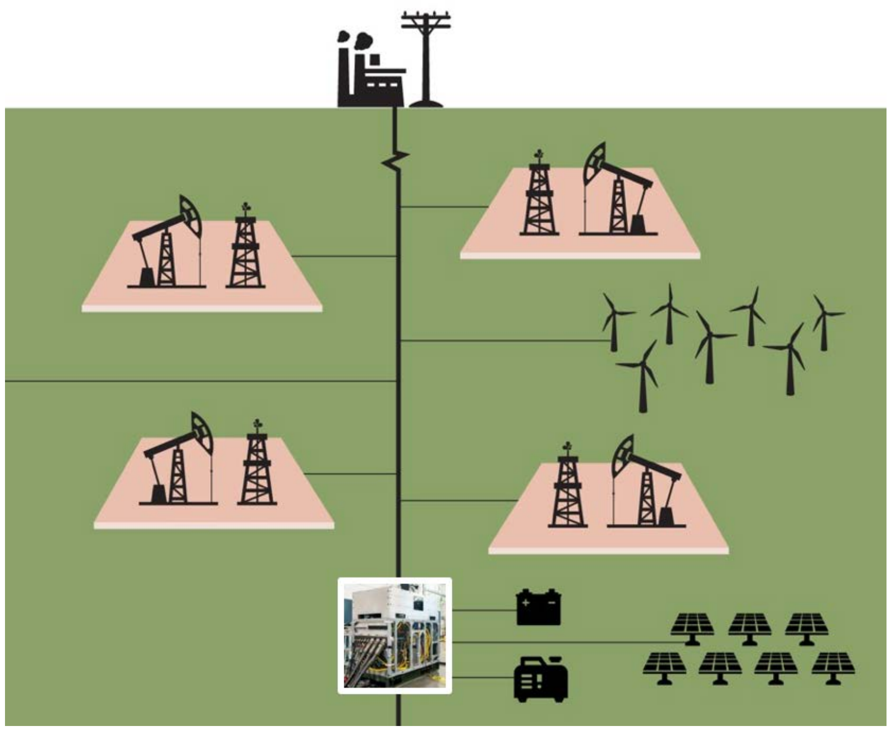

Figure 4. Schematic for a comprehensive approach to electrification of the wellpad and platform via microgrids

Oil operations are frequently conducted in areas with available renewable energy resources. Oil field and wellpad equipment could be converted to electric power and then connected via a microgrid with a controller that optimizes multiple clean power sources (see Figure 4). This approach has been successfully implemented at remote military bases, communities, and islands and could be adapted to such an industrial process with known energy demands and available resources. Power sources could consist of solar PV/wind systems, fuel cells, energy storage, hydrogen, field gas, or even grid power. This approach reduces leaks and emissions, provides resiliency during outages, and optimizes for least cost.

A notable example of where renewable technologies can be integrated into upstream operations is to power artificial lift pumps. When there is not enough well pressure for oil to flow to the surface, a rod beam artificial lift pump—often referred to as a "sucker rod pump" or a "Jack pump"—is used to assist extraction.[3] In many areas, rod beam pumps are used extensively. For example, more than 80% of oil production wells operating in the western United States are installed with a rod beam pump (Endurthy, Kialashaki and Gupta 2016). Solar power, combined with a capacitor to store regenerative power during the rod down-stroke, can be used to power a rod beam pump. Test cases have shown significant potential energy savings (Endurthy, Kialashaki and Gupta 2016), and solar powered oil pumps are now beginning to see commercial operation (Healing 2015). Combined with battery storage, solar power pumps could be applicable to off-grid locations with sufficient sunlight.

5.2 Renewable-Energy-Powered Secondary Recovery

Renewable generation can be especially well suited to powering water injection pumps to stimulate oil recovery because production from water injection is not significantly affected by injection variability (Feller 2017). An especially important potential application is using offshore wind power to power water injection pumps.

By one analysis, offshore wind was found in 2012 to be an economic and environmentally sound option for supplying electricity to offshore oil and gas platforms in some cases (Korpas, et al. 2012). Costs for offshore wind generation have fallen significantly since then and are anticipated to continue to decrease as the technology matures. The average strike price for European offshore wind projects that come online between 2021 and 2025 is less than half the strike price for similar projects that have or will come online between 2016 and 2020 (Musial, et al. 2017). As wind costs fall, it will become economically attractive to substitute power from diesel and gas generators with power from wind platforms. Finally, wind integration reduces carbon emissions, which can be beneficial to countries that are attempting to meet climate targets and in areas that price carbon emissions.

Wind-powered water injection can provide water injection far from the platform, which reduces the need for lengthy water injection lines and can eliminate the need for costly modifications for oil platforms not initially designed for water injection. The Wind Powered Water Injection project recently completed an initial testing phase in which it was shown that wind power can provide water injection at competitive prices (Feller 2017).

5.3 Concentrating Solar and Geothermal Heat for Tertiary Recovery (EOR)

Tertiary recovery, or EOR, presents several opportunities for renewable integration. Renewable technologies can both provide energy for and generate energy from EOR processes. Land and

[3] For more information about sucker-rod lifts and beam-pumping systems, see http://petrowiki.org/Sucker-rod_lift.

solar irradiance permitting, concentrated solar can be an economic means of generating steam for EOR. Geothermal cogeneration can also produce electricity from latent heat in wells.

Thermal EOR consists of injecting steam into the oil reservoir to facilitate flow by reducing the viscosity of the oil. Natural gas is used as an energy source to produce steam, which is then injected into the reservoir. Solar thermal EOR substitutes natural gas with concentrated solar power (CSP) as the energy source for producing steam (Zhong and Bazilian 2018). Trough-shaped mirrors, sometimes housed in a protective greenhouse, concentrate sunlight to generate steam with temperatures up to 640°F (Sandler, Fowler, et al. 2014).

CSP technologies are well suited for thermal EOR. There is significant overlap between regions with high solar radiation and large petroleum reserves (Wang, O'Donnell and Brandt 2017). Due to latent heat stored in the reservoir rock, oil recovery rates were found to not be greatly impacted by solar variability (Sandler, Fowler, et al. 2012). Finally, solar thermal EOR has lower capital costs than CSP for electricity generation because solar thermal EOR does not require a turbine to convert steam to electricity, which greatly reduces project cost and complexity.

While CSP capital costs are significantly higher than for a comparable natural gas system, fuel cost savings have been found to make solar thermal EOR competitive with traditional natural gas EOR in some cases (Sandler, Fowler, et al. 2014). The profitability of solar thermal EOR relative to alternatives varies with natural gas prices, cost of capital, and field characteristics, such as the amount of solar radiation and expected field lifetime. There is generally an alignment between oil reserves and solar potential, especially among countries in the Middle East. Estimates for solar thermal projects used for petroleum EOR could be economically viable and range from 19–44 gigawatts (GW) (Wang, O'Donnell and Brandt 2017).

The technology for integrating CSP into oil production is now commercially viable in some locations. The first major project to integrate CSP into oil production was in California through former Chevron subsidiary BrightSource (Moritis 2011). The pilot project began operation in 2011 and operated for 4 years.

More recently, the Miraah project—a $600 million joint venture initiated in 2015 between the government of Oman and the company GlassPoint Solar—has begun producing solar steam for the Amal oilfield. When completed, the project will be the largest concentrated solar project in the world, with a capacity exceeding 1 GW and a production of 6,000 tons of steam per day (Wesoff 2015). Successful completion and operation of the Miraah project would prove the economic viability of solar thermal EOR at scale and lead to the adaption of similar projects in other locations.

Mature oil wells can produce up to 50 barrels of water per barrel of oil (Xin, et al. 2012). Water extracted from a well has naturally raised temperatures due to geothermal heating. While for most wells the heating is not significant—80% of wells have temperatures below 176°F (80°C)—in some instances, temperatures can exceed 400°F (~200°C) (Augustine and Falkenstern 2012). Steam can be used to generate electricity, provide field heating, and can be reinjected for EOR. While near-term prospects for geothermal cogeneration are limited, in some cases they can provide economic benefits (Augustine and Falkenstern 2012). In addition to heat and electricity generated, geothermal cogeneration has the additional benefit of extending field life. Extending a field's lifetime delays well abandonment costs, which improves field economics.

Steam injection and geothermal energy have important synergies. Steam injection leads to higher produced water temperatures than for conventional fields (Ziabakhsh-Ganji, et al. 2018). Additional energy requirements for steam injection also lead to greater demand for the electricity and heat produced from geothermal generation (Ziabakhsh-Ganji, et al. 2018). A trend toward deeper wells, which produce higher water temperatures, an increased use of steam injection EOR, and an increase in the pricing and regulation of carbon emissions indicate a growing opportunity for geothermal cogeneration in the future.

6 Midstream: Renewable Integration in Oil and Gas Transportation

Midstream transportation uses less energy than upstream or downstream operations and correspondingly has the smallest potential for renewable integration (Halabi, Al-Qattan and Al-Otaibi 2015). Furthermore, oil transportation by ship, rail, and truck currently have limited opportunities for renewable technologies. That being said, there are still several opportunities for renewable technologies to have a meaningful impact on operation costs and emissions.

A vast network of pipelines transport oil and gas from producers to refineries and end users. In the United States alone there are more than 300,000 miles of mainline natural gas pipelines with 1,400 compressor stations (Federal Energy Regulatory Commission 2015) and approximately 55,000 miles of crude oil trunk lines and 95,000 miles of refined products pipelines, which combined transport more than 40 million barrels of liquids per day (Pharris and Kolpa 2007). Figure 5 displays the U.S. natural gas transportation network along with major fields. As can be seen, pipelines can transport supply significant distances from production areas to major demand hubs.

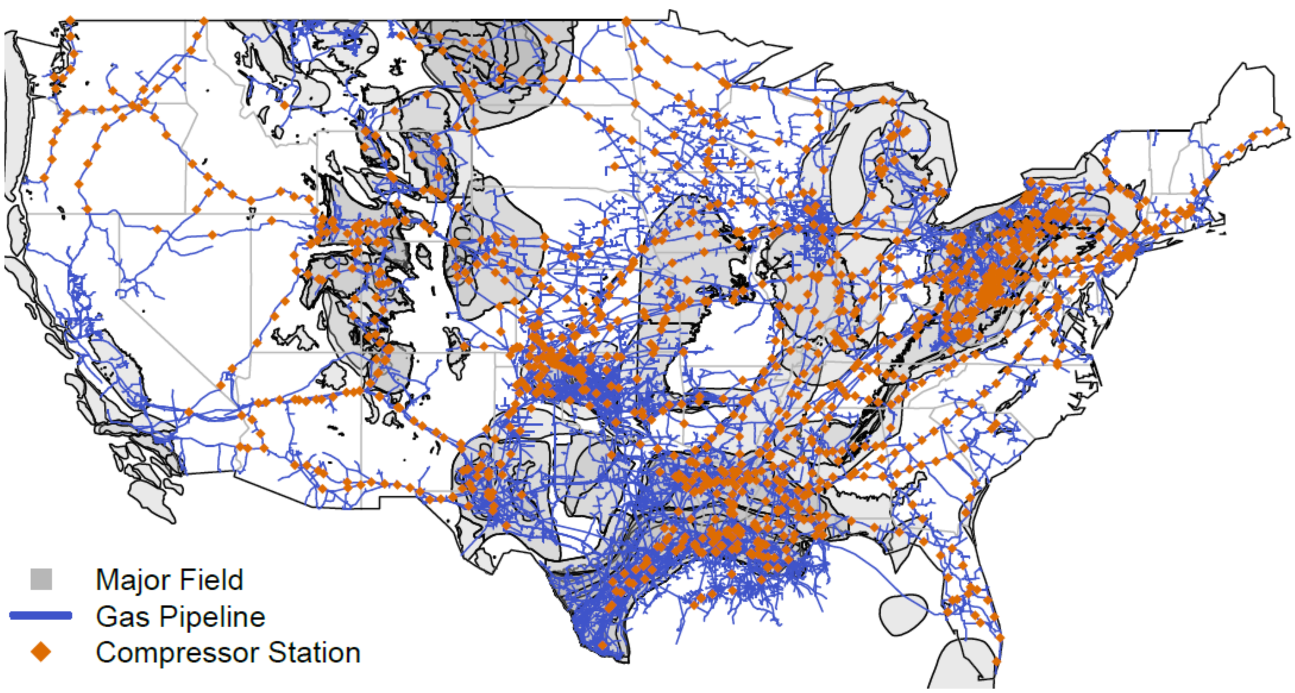

Figure 5. Natural gas transportation system. ***Figure produced using data from*** **(EIA 2018)**

Renewable technologies are already integrated into some pipeline operations, with solar energy powering sensors and providing cathodic corrosion protection[4] (Pharris and Kolpa 2007). However, as renewable costs decline and the technologies improve, additional opportunities for

---

[4] A cathodic protection system uses charged anodes attached to the pipe to prevent the pipe from corroding.

integration arise. One of the opportunities is natural gas pipeline compressor electrification, compressor heat recovery, and electricity production from expansion turbines.

6.1 Compressor Electrification

As most oil pumping stations use electric motors for the prime mover, these systems are automatically using more renewable power as the grid greens (Pharris and Kolpa 2007). Natural gas pipelines, however, are primarily powered by gas engines or turbines (Greenblatt 2015). Replacing gas engines and turbines with electric motors could increase renewable integration and reduce noise, fuel use, and emissions.

Electric motors have low operating costs and more efficiently accommodate a wide throughput range than gas engines or turbines (Greenblatt 2015). As natural gas plants are ramped to account for increased variable generation, the variability of natural gas demand will increase, meaning pipelines will likely deal with larger swings in throughput. This trend supports the use of more electric motors to power natural gas compressor stations.

An important barrier to using electric motors to power compressor stations is a concern of reliability. While electric motors are highly reliable, the electric grid does not always meet the operation standards of the oil and gas industry, especially in remote areas where compressor stations are often located (Greenblatt 2015). Work on increasing grid reliability, reductions in the price of microgrid technologies, and rewarding lower emissions from electric motors could help motivate a shift toward using more electric motors.

6.2 Compressor Heat Recovery

Gas turbines used to power natural gas compressor stations generate a considerable amount of heat. In some cases, this heat can be reused to generate power or used in industrial processes. There are currently 12 power generation systems, totaling 64 MW of electricity capacity, installed at natural gas compressor stations in the United States (Elson, Tidball and Hampson 2015). An estimated 40 MW worth of potential additional projects currently offer expected paybacks of less than 5 years (Elson, Tidball and Hampson 2015). However, changes in market conditions could significantly increase the economic opportunity for compression station heat recovery. Estimates of the technical potential for electricity generated from compressor station heat recovery range from 500 MW (Hedman 2008) to 1.1 GW (Elson, Tidball and Hampson 2015). As economies of scale are present, large systems with high utilization rates are most applicable (Hedman 2008).

A disadvantage of compressor cogeneration is the variability of output. Compressor stations do not always run and therefore would not always generate heat or electricity (Greenblatt 2015). If extracted heat is used for industrial processes, then an associated process must be able to operate with variable heat. Similarly, if electricity generated provides off-grid power, then the consumer must be able to handle variable generation.

6.3 Turboexpanders

Compressors raise the gas pressure to between 500 and 1,400 pounds per square inch (psi) to transport natural gas long distances. While higher pressures increase the economics of transportation, and while power plants and some industrial customers use high pressure gas, most customers require pressures well under 10 psi (CPS Energy 2011). The potential energy created from raising pipeline pressure is lost when the pressure is stepped down at distribution hubs. A turboexpander can capture this potential energy to generate electricity.

Turboexpanders are used in a variety of industry applications. Unfortunately, they are generally considered uneconomic for use in natural gas pipelines under current market conditions (Greeenblatt 2015; Hedman 2008). Primary challenges include the required cost of preheating the gas before expansion and pipeline operations causing variability in output (Hedman 2008). Turboexpanders have the benefits of being a proven technology that emits significantly less criteria and other gasses per megawatt-hour generated compared to coal and gas power plants. Turboexpanders may therefore see economic opportunities in regions that price or regulate emissions.

7 Downstream: Renewable Integration in Oil Refining

Oil refining is a complicated process that requires large capital investments and has significant energy requirements. The refining process requires heating oil to break carbon bonds and remove impurities. More than 90% of energy use in refining goes toward direct heating and steam generation (Brueske, Sabouni and Zach 2012). As Figure 6 shows, the majority of energy used in the petroleum supply chain is from burning onsite oil to process and refine petroleum. Due to the large production volumes and high temperatures required, petroleum refining is the largest consumer of fuel and the largest generator of onsite greenhouse gas emissions in the U.S. manufacturing sector (Halabi, Al-Qattan and Al-Otaibi 2015; Brueske, Sabouni and Zach 2012; EPA 2018).

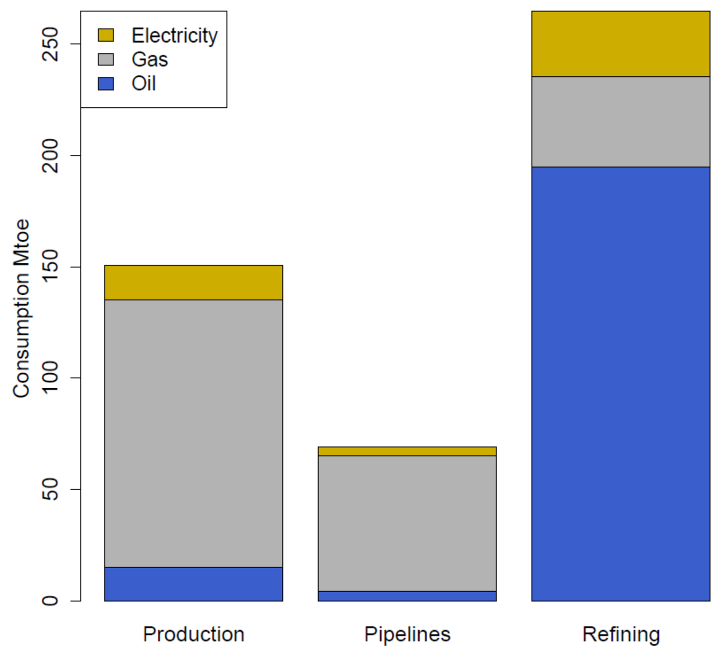

Figure 6. Energy consumption in oil and gas industry. ***Adapted from*** **(Halabi, Al-Qattan and Al-Otaibi 2015)**

Energy usage in the refining process is a major operations cost. In 2010, the U.S. petroleum refining industry spent $9 billion on energy purchases, equating to roughly 50% of total non-capital costs (Worrell, Corsten and Galisky 2015). Furthermore, due to shifts toward increasingly heavy and sour oil, refining energy requirements are rising (Karras 2010). Emissions from refineries also increase as oil quality decreases, which increases the difficulty of meeting environmental regulations (Karras 2010).

Oil refineries can incorporate renewable energy technology into operations by using renewable sources to generate heat and electricity, and to produce hydrogen that is an input in the refining process. Oil refineries can also use excess heat to generate electricity.

7.1 Renewables to Generate Heat and Power

Each step along the refinery process requires different temperatures and pressures. Oil is first heated to 200–300°F (90–150ºC) and washed with water to remove salt and other suspended solids (Worrell, Corsten and Galisky 2015). Atmospheric distillation then separates products based on their boiling point in the crude distillation unit (CDU), where crude oil is heated to temperatures around 750°F (390ºC) (Worrell, Corsten and Galisky 2015). Heavy fuel oils are further treated in the vacuum distillation unit (VDU) at temperatures between 730 and 850°F (390 and 450ºC) (Worrell, Corsten and Galisky 2015). The low-pressure environment of the VDU lowers the heavy oil boiling point to facilitate separation. Additional processing occurs in the fluid catalytic cracker (FCC), the hydrocracker, and coking unit. Each of these processes separate heavier oil products into lighter and more valuable products.

Hydrotreating mixes hydrogen with the feedstream at temperatures between 500 and 800°F (260 and 460ºC) to remove sulfur (Worrell, Corsten and Galisky 2015). A catalytic reformer uses a catalytic reactor to produce high octane gasoline and hydrogen. Additional processes, such as alkylation, which uses steam, power, and various acids to produce alkylates, are also common. Figure 7 displays yearly estimated energy use by refining process for U.S. refineries in 2012. Hydrotreatment and the CDU account for nearly 50% of total energy requirements.

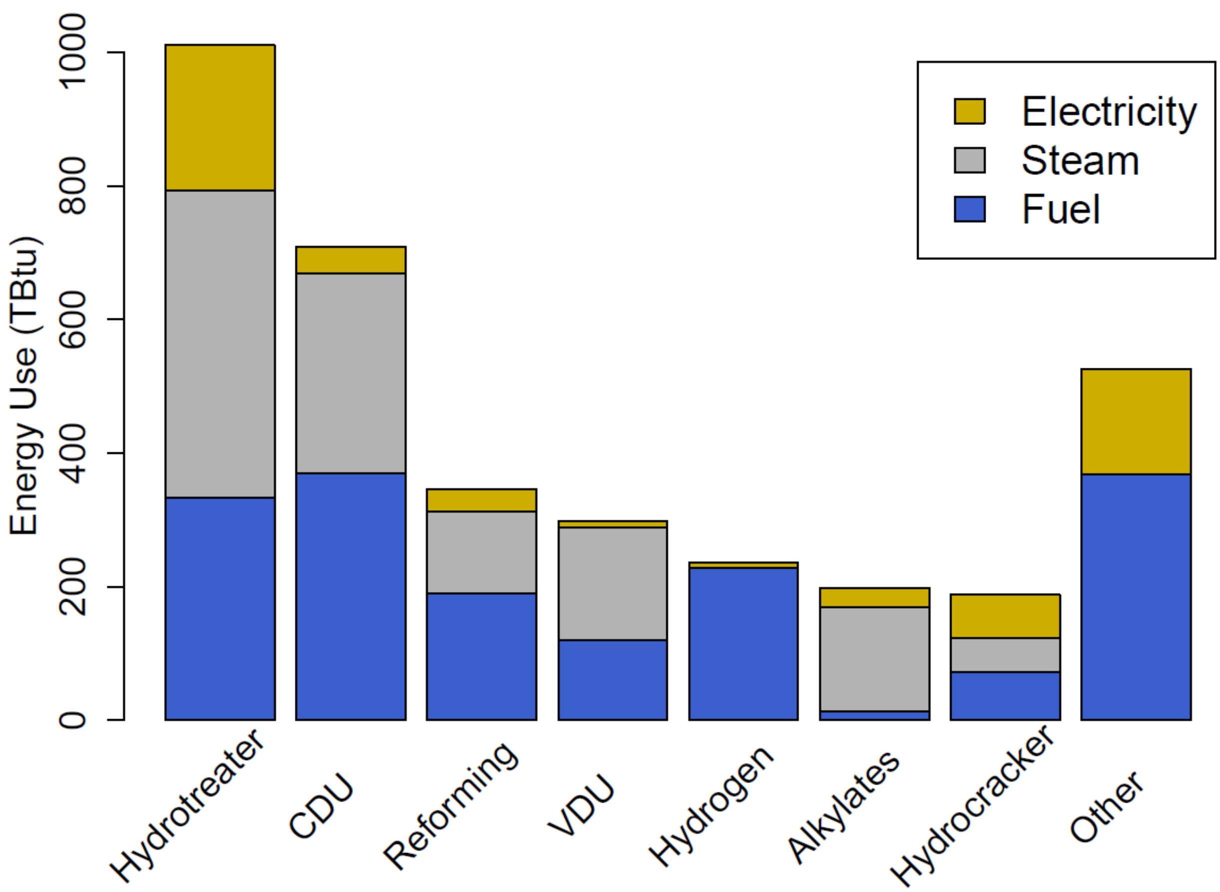

Figure 7. Energy use by refinery process. *Figure adapted from* (Worrell, Corsten and Galisky 2015)

When land and sufficient sunlight are available, CSP can be used to produce heat and steam. While CSP may be unsuited for some high-end temperature requirements, steam production and heating up to 750°F (400ºC), and in some cases up to 1,020°F (550ºC), can be provided by current CSP technologies (Kurup and Turchi 2015). While most refineries do not meet the criteria of having both available land and abundant sunlight, the potential for CSP integration is still large due to the significant energy intensity of oil refining. Estimated market potential for solar thermal used in oil refining range between 21 and 95 GW (Wang, O'Donnell, and Brandt 2017). Along with high heat requirements, oil refineries have large electricity loads. Increasing the renewable energy used to run machinery, such as compressors, pumps, circulators, and controllers, can reduce operation costs and carbon emissions.

7.2 Hydrogen Production

Refineries use hydrogen in several production processes. Most importantly, hydrogen is used in the hydrotreatment process to lower the sulfur content of diesel fuel. Refinery demand for hydrogen has increased as demand for diesel fuel has risen and sulfur-content regulations have become more stringent (Hicks and Gross 2016). Hydrogen used in the refining process increased by more than 50% between 2008 and 2014 (Hicks and Gross 2016).While hydrogen is produced as a co-product of the catalytic reformation of gasoline, demand for hydrogen exceeds supply produced from the refining process itself (Philibert, Cédric 2017).

Hydrogen is produced primarily through steam-reforming natural gas (Likkasit, et al. 2016). Concentrated solar energy can complement or replace conventional fuel as the heating source for this process (Likkasit, et al. 2016). Hydrogen produced by electrolysis powered by renewable generation can also be used to meet oil refinery demand (Philibert, Cédric 2017). Costs of hydrogen production from renewables is currently higher than conventional production methods (Likkasit, et al. 2016). However, if renewable generation costs continue to fall, and if regulations on greenhouse gas emissions increase, hydrogen production may become an effective means of using renewable technologies to reduce costs and reduce emissions from oil and gas operations.

7.3 Power Cogeneration

Oil refining runs at high temperatures and elevated pressures. This offers numerous opportunities for heat recovery and power recovery. Cogeneration is already common within the refining industry, representing almost 13% of all industrial cogenerated electricity (Worrell and Galitsky 2005). However, the potential for cogeneration is still far from being fully exploited. Power recovery systems can reduce a refinery's energy intensity by 7%–10% (Worrell, Corsten and Galisky 2015).

The primary application for power recovery is with the FCC (Worrell, Corsten and Galisky 2015). The hydrocracking process presents another opportunity for power recovery. Power is generated from the pressure difference between the reactor and fractionation stages (Worrell, Corsten and Galisky 2015). Integration of a turboexpander on the hydrocracker at the Zeeland Refinery in the Netherlands produces 73,000 MWh per year, resulting in a payback period of less than 3 years (Worrell, Corsten and Galisky 2015).

Power recovery offers a means of reducing the energy and carbon intensity of the refining process. For many refineries, cogeneration can already offer positive economic returns. If the industry seeks to further reduce air emissions, cogeneration may become increasingly beneficial as well.

8 Conclusion

As oil and gas production shifts toward lower quality and unconventional reserves, energy use and emissions from operations are likely to grow in the future. Furthermore, oil and gas operations are energy intensive which can have negative environmental impacts. Integrating renewable energy technologies into oil and gas operations offers a means of reducing fossil fuel use in the production of oil and gas, which can both lower operation costs and reduce emissions as well as conserve petroleum production for higher value uses. In some cases, renewable integration can currently provide a cost-effective and environmentally beneficial way of meeting operations energy requirements. If costs of renewable technology continue to fall, the benefits of renewable integration would continue to increase.

Renewable technologies can be integrated in all links of the oil and gas supply chain. For upstream oil and gas production, the primary applications identified are solar heating for EOR and other heating requirements, offshore wind to power offshore operations, wellpad electrification from solar and wind, and geothermal cogeneration from oil fields. Solar thermal generation for EOR and wellpad electrification are already seeing commercial operation. Wind power for offshore water injection and geothermal energy production are close to commercial operation as well. Combined, these technologies will be useful tools to reduce operation costs and emissions.

While midstream transportation offers the fewest opportunities by size of demand for renewable integration, renewable technologies can still be beneficially integrated. The use of electric motors to power natural gas compressors reduces emissions and reduces operation and maintenance costs. Heat recovery is already economic for large compressor stations, and turboexpanders may be an economic option as technology continues to advance and operation cost environments evolve.

Oil refineries are the largest consumer of fuel in U.S. manufacturing and the largest generator of onsite greenhouse gas emissions in the manufacturing sector. Fuel costs also constitute half of all operations costs. Renewable technologies can be integrated to reduce fuel expenditures. Where land and sunlight are available, solar heating may be used. Renewable energy may also be used to produce hydrogen by electrolysis. Finally, further use of power recovery can reduce emissions and fuel costs.

While significant challenges exist to integrating renewable energy technologies into oil and gas operations, there are also significant economic opportunities for renewable technologies in the petroleum industry. Falling costs and growing energy intensity and environmental concerns are all leading to more compelling reasons for integrating renewable energy technologies. Oil and gas operators would be well served by further analysis of where renewable technologies can be beneficially integrated and by working toward further integrating renewable technologies into current and future operations.

References

Abromova, Anna, Vladimir Abramov, S Kuleshov, and E Timashev. 2014. "Analysis of the Modern Methods for Enhanced Oil Recovery." In *Energy Science and Technology*, 118-148.

Augustine, Chad, and David Falkenstern. 2012. "An Estimate of the Near-Term Electricity Generation Potential of Co-Produced Water From Active Oil and Gas Wells." *GRC Transactions* 36.

Bluestein, Joel, Hemant Mallya, Louis Yandoli, Michael Polchert, and Natalie Amarin. 2015. *Methane Emissions from the Oil and Gas Industry: ``Making Sense of the Noise".* ICF International.

BOEM. 2017. *Bureau of Energy and Ocean Management.* Accessed 2017. https://www.boem.gov/.

Brueske, Sabine, Ridah Sabouni, and Chris Zach. 2012. *U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis.* Energetics Incorporated, Department of Energy.

CIA World Factbook. 2017. *Crude Oil - Proved Reserves.* Accessed 4 19, 2018. https://www.cia.gov/library/publications/the-world-factbook/rankorder/2244rank.html.

Clark, C E, J Han, A Burnham, J B Dunn, and M Wang. 2011. *Life-Cycle Analysis of Shale Gas and Natural Gas.* Argonne National Laboratory.

CPS Energy. 2011. *Summary of Gas Service Standards for Engineers, Architects, Contractors and Developers.* CPS Energy.

Devold, Havard. 2013. *Oil and Gas Production Handbook An Introduction to Oil and Gas Production, Transport, Refining and Petrochemical Industry.* ABB.

EIA. 2018. *Layer Information for Interactive State Maps.* Energy Information Administration. Accessed April 15, 2018. https://www.eia.gov/maps/layer_info-m.php.

El-Katiri, Laura, and Bassam Fattouh. 2017. *A Brief Political Economy of Energy Subsidies in the Middle East and North Africa.* International Development Policy.

Elson, Amelia, Rick Tidball, and Anne Hampson. 2015. *Waste Heat to Power Market Assessment.* ICF International.

Endurthy, Akhilesh, Arash Kialashaki, and Yeshpal Gupta. 2016. *Solar Jack Emerging Technologies Technical Assessment.* Pacific Gas and Electric Company.

Energy Information Administration. 2016 . *Trends in U.S. Oil and Natural Gas Upstream Costs.* Department of Energy.

EPA. 2018. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.* Environmental Protection Agency.

Fattouh, Bassam, and Laura El-Katiri. 2012. *Energy Subsidies in the Arab World.* United Nations Development Program.

Federal Energy Regulatory Commission. 2015. *Energy Primer: A Handbook of Energy Market Basics.* FERC.

Feller, F. 2017. "WIN WIN - Wind-Powered Water Injection." Offshore Mediterranean Conference and Exhibition.

Freise, Jon. 2011. "The EROI of Conventional Canadian Natural Gas Production." *Sustainability* 3 (11): 2080-2104.

Greenblatt, Jeffery. 2015. *Opportunities for Efficiency Improvements in the U.S. Natural Gas Transmission, Storage and Distribution System.* Berkeley: Ernest Orlando Lawrence Berkeley National Laboratory.

Halabi, M, A Al-Qattan, and A Al-Otaibi. 2015. "Applications of Solar Energy in the Oil Industry--Current Status and Future Prospects." *Renewable and Sustainable Energy Reviews* 43: 296-314.

Healing, Dan. 2015. "Producer Builds Solar Array to Power Nodding Prairie Pumpjack." *Calgary Herald.*

Hedman, Bruce. 2009. *Status of Waste Heat to Power Projects on Natural Gas Pipelines.* ICF International.

Hedman, Bruce. 2008. *Waste Energy Recovery Opportunities for Interstate Natural Gas Pipelines.* ICF International.

Hicks, Susan, and Peter Gross. 2016. *Hydrogen for Refineries is Increasingly Provided by Industrial Suppliers.* EIA.

Hirtenstein, Anna. 2017. "Big Oil Becomes Greener With Progress in Cutting Pollution." *Bloomberg.*

International Energy Agency. 2017. *World Energy Outlook 2017.* IEA.

IPCC. 2018. "Summary for Policymakers." In *Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels*, 1-35. Cambridge University Press.

Karras, Greg. 2010. "Combustion Emissions from Refining Lower Quality Oil: What is the Global Warming Potential." *Environmental Science* 44: 9584-9589.

Korpas, Magnus, Leif Warland, Wei He, Tande, and John. 2012. "A Case-Study on Offshore Wind Power Supply to Oil and Gas Rigs." *Energy Procedia* 24: 18-26.

Kurup, Parthiv, and Craig Turchi. 2015. *Initial Investigation into the Potential of CSP Industrial Process Heat for the Southwest United States.* NREL.

Lazard. 2017. *Lazard's Levelized Cost of Energy Analysis - Version 11.0.* Lazard.

Likkasit, Chonnawee, Azadeh Maroufmashat, Ali Elkamel, and Hong-ming Ku. 2016. "Integration of Renewable Energy into Oil & Gas Industries: Solar-aided Hydrogen Production." *International Conference on Industrial Engineering and Operations Management.* Detroit.

Liss, William, and Patricia Rowley. 2018. *Assessment of Natural Gas and Eclectric Distribution Service Reliability.* Des Plaines, Illinois: Gas Technology Institute.

Moritis, Guntis. 2011. "Chevron Starts California Demo of Solar-to-Steam Enhanced Recovery." *Oil & Gas Journal.*

Musial, Walter, Philipp Beiter, Paul Schwabe, Tian Tian, Tyler Stehly, and Paul Spitsen. 2017. *2016 Offshore Wind Technologies Market Report.* U.S. Department of Energy.

Pharris, T.C., and R.L Kolpa. 2007. *Overview of the Design, Construction, and Operation of Interstate Liquid Petroleum Pipelines.* Argonne National Laboratory.

Philibert, Cédric. 2017. *Renewable Energy For Industry: From Green Energy To Green Materials and Fuels.* International Energy Agency.

Quinlan, Eric, Robert Kuilenburg, Tom Williams, and Gerhard Thonhauser. 2011. "The Impact of Rig Design and Drilling Methods on the Environmental Impact of Drilling Operations." American Association of Drilling Engineers.

REN21. 2017. *Renewables 2017 Global Status REport.* Paris: REN21.

Robinson, Paul, and Geoffrey Dolbear. 2007. "Hydrotreating and Hydrocracking: Fundamentals." In *Practical Advances in Petroleum Processing*, 177-218. Springer.

Sandler, Joel, Garrett Fowler, Kris Cheng, and Anthony Kovscek. 2014. "Solar-generated Steam for Oil Recovery: Reservoir Simulation, Economic Analysis, and Life Cycle Assessment." *Energy Conversion and Management* 77: 721-732.

Sandler, Joel, Garrett Fowler, Kris Cheng, and Anthony Kovscek. 2012. *Solar-Generated Steam for Oil Recovery: Reservoir Simulation, Economic Analysis, and Life Cycle Assessment.* Society of Petorleum Engineers.

Sovacool, Benjamin. 2017. "Reviewing, Reforming, and Rethinking Global Energy Subsidies: Towards a Political Economy Research Agenda." *Ecological Economics 135* 135: 150-163.

Tripathi, Vinay, and Adam Brandt. 2017. "Estimating Decades-Long Trends in Petroleum Field Energy Return on Investment (EROI) With an Engineering-Based Model ." *Plos One* 12.

Veld, Klaas, and Owen Phillips. 2010. "The Economics of Enhanced oil Recovery: Estimating Incremental Oil Supply and CO2 Demand in the Powder River Basin." *Energy Journal* 31 (3): 31-55.

Wang, Jingfan, John O'Donnell, and Adam Brandt. 2017. "Potential Solar Energy Use in the Global Petroleum Sector." *Energy* 118: 884-892.

Wesoff, Eric. 2015. "GlassPoint is Building the World's Largest Solar Project in an Omani Oil Field." *Greentech Media.*

World Bank. 2016. *Global Solar Atlas.* Accessed 4 17, 2018. http://globalsolaratlas.info/downloads/world.

World Bank. 2016. *State and Trends of Carbon Pricing.* Washington, D.C.: World Bank, Ecofys and Vivid Economics.

Worrell, Ernst, and Christina Galitsky. 2005. *Energy Efficiency Improvements in the Petroleum Refining Industry.* Berkeley: Ernest Orlando Lawrence Berkeley National Laboraory.

Worrell, Ernst, Marielle Corsten, and Christina Galisky. 2015. *Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries: An ENERGY STAR Guide for Energy and Plant Managers.* United States Environmental Protection Agency.

Xin, Shouliang, Hongbin Liang, Bing Hu, and Kewen Li. 2012. "Electrical Power Generation From Low Temperature Co-Produced Geothermal Resources at Huabei Oilfield." *Thirty-Seventh Workshop on Geothermal Reservoir Engineering.*

Zhong, Minjia, and Morgan Bazilian. 2018. "Countours of the Energy Transition: Investment by International Oil and Gas Companies in Renewable Energy." *The Electricity Journal* 31: 82-91.

Ziabakhsh-Ganji, Zaman, Hamidreza Nick, Marinus Donselaar, and David Bruhn. 2018. "Synergy Potential for Oil and Geothermal Energy Exploitation." *Applied Energy* 212: 1433-1447.