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A review of solar and geothermal applications of renewable energy-driven enhanced oil recovery

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Abstract

This critical review explores status, technical configurations, and feasibility of integrating geothermal and solar energy sources for Enhanced Oil Recovery (EOR) activities. Traditional thermal EOR activities, most prominently steam injection activities such as steam flooding and cyclic steam stimulation (CSS), have a recorded utilization of between 0.25–0.3 MMBtu of natural gases per all-recoverable-barrel of crude, equating to more than 0.3–0.5 tons of CO_2 emissions per all-recoverable-barrel. As a panacea to this quandary, renewable-powered EOR has proven a viable solution. At its center, Oman's Glass Point Mirah solar plant reflects that covered or protected parabolic trough technologies hold humongous potential in supplying more than 1,000 MTh of steam while registering remarkable reductions in utilization of natural gases. Analogously, geothermal utilization in California's San Joaquin Valley has registered humongous reductions in utilization of fossil fuels through utilization of co-produced geothermal fluids for injection of heat. Hybrid configurations of solar-geothermal have also had their assessment, which, upon simulations of variously modeled configurations, are able to register utilization reductions of natural gases by a maximum rate of 80% while realizing payback periods of 4.7 years for optimal configurations. Though steeped in promising results, full-scale adoption faces technical barriers premised upon thermal utilization, corrosion barriers emanating premised upon geothermal brines, initial high investments, and few policy advantages. Technological innovations including advanced thermal storage, corrosion-proofing, and modulable solar-geothermal systems are here identified here as influential activators. Pilot-scale demonstrations, lifecycle assessments, and robust policy climates are also here recommended towards improvement upon adoption rate. Such synthesis here positions solar and geothermal-powered EOR on the viable but little-exploited pathway towards upstream crude production's decarbonizing.

Keywords: Renewable Energy Integration; Enhanced Oil Recovery (ERO); Solar Thermal Energy; Geothermal Energy; Hybrid Solar-Geothermal Systems

1. Introduction

Enhanced Oil Recovery (EOR) encompasses a range of techniques used to increase the amount of crude oil extracted from reservoirs beyond what is achievable through primary and secondary recovery methods [1]. Conventional EOR methods including thermal, chemical, and gas injection require significant energy inputs, often relying on fossil fuels such as natural gas to generate steam or drive compressors. While these processes have contributed substantially to

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extending the productive life of mature oil fields, they also result in considerable greenhouse gas emissions and high operating costs, challenging the environmental sustainability of oil production [2]. In recent years, the global energy sector has faced mounting pressure to reduce carbon footprints and transition to more sustainable practices. This imperative has sparked growing interest in integrating renewable energy sources into oil and gas operations. Among the renewable options, solar and geothermal energy stand out as promising candidates for supplying thermal energy required in EOR processes [3].

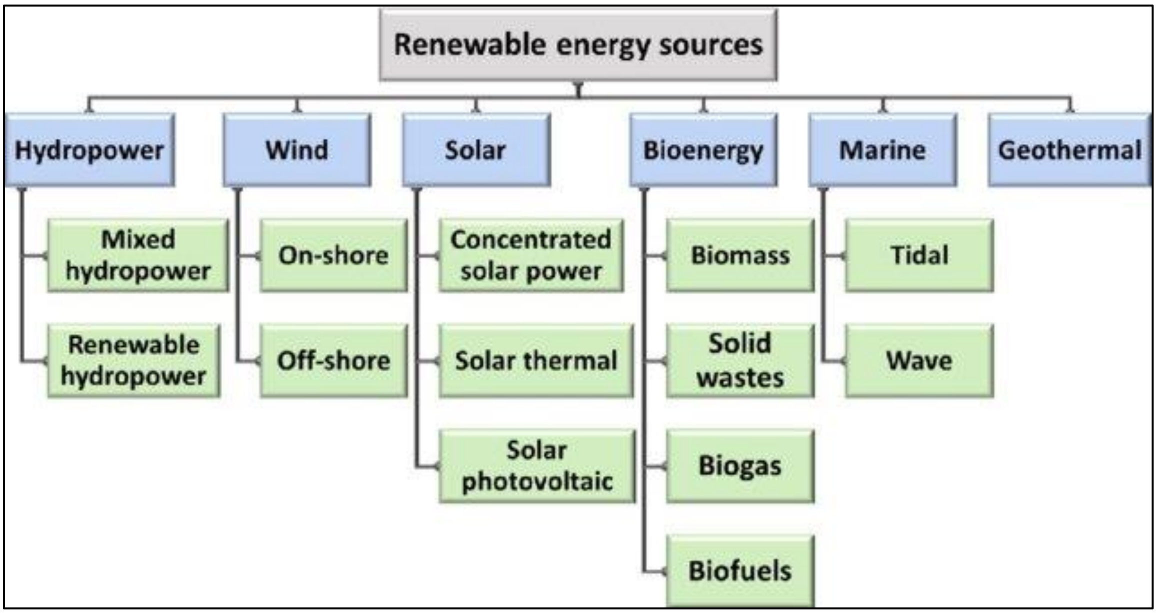

Figure 1 Different types of renewable energy. The field of renewable energy technology encompasses various methodologies, including solar, wind, geothermal, biomass, and hydropower energy generation. Integrating renewable energy into the electricity grid is crucial to addressing global climate change [4]

Solar thermal technologies can generate high-temperature steam by concentrating solar radiation, while geothermal resources offer a reliable source of subsurface heat that can be directly harnessed for injection into reservoirs [5]. The application of renewable-powered EOR is still in its early stages, with only a handful of field demonstrations and limited large-scale deployments globally. Nonetheless, pilot projects such as the Glass Point Solar facility in Oman have illustrated the technical feasibility and potential economic benefits of these approaches. Integrating renewable sources into EOR operations could significantly reduce fuel consumption, mitigate emissions, and improve the long-term sustainability of oil production in regions with abundant solar irradiation or geothermal resources [6]. This review aims to systematically examine the current state of solar and geothermal applications in renewable energy-driven EOR. Specifically, the objectives are to; Summarize the fundamental principles and technologies underpinning solar and geothermal EOR, Analyze operational configurations, performance metrics, and cost considerations, Highlight case studies and field deployments demonstrating practical implementation, Identify the key technical, economic, and regulatory challenges constraining broader adoption, Propose research directions and recommendations to accelerate the development of renewable-powered EOR systems. By synthesizing recent advances and gaps in knowledge, this review contributes to a deeper understanding of how solar and geothermal energy can support the decarbonization of oil recovery processes and inform future innovation in this underexplored field.

1.1. Verified Data and Field Performance Insights

Thermal EOR processes, especially steam flooding and cyclic steam stimulation (CSS), are highly energy-intensive, consuming approximately 0.25–0.3 MMBtu of fuel per barrel of oil and resulting in greenhouse gas emissions of 0.3–0.5 tons of CO_2 per barrel produced [7]. Solar thermal technologies such as parabolic troughs and Fresnel reflectors can replace or offset this energy demand. For instance, the Glass Point Mirah solar EOR project in Oman employs enclosed parabolic troughs to generate over 1,000 MW^g of steam capacity, significantly cutting natural gas consumption and achieving up to 80% emissions reduction during peak solar periods [8]. Similarly, geothermal EOR practices in California's San Joaquin Valley and pilot efforts in Indonesia and China have leveraged co-produced geothermal fluids for steam generation, yielding measurable reductions in both operational costs and emissions [9]. Furthermore, hybrid solar-geothermal systems offer synergistic benefits. For example, modeling by [10] on a solar-boosted geothermal flash cycle demonstrated a desalinated water production rate of 28.46 kg/s, an energetic efficiency of 21.9%, and a payback period of only 4.74 years, highlighting the economic viability of combined systems. These real-world examples affirm the potential of solar and geothermal integration in advancing cleaner and more efficient oil recovery.

2. Fundamentals of Renewable-Powered Enhanced Oil Recovery

Enhanced Oil Recovery (EOR) methods are implemented to increase oil production by improving the mobility of hydrocarbons and reducing residual oil saturation in reservoirs [11]. Among the different EOR techniques, thermal methods are the most energy-intensive and account for a significant share of incremental oil production globally, particularly in heavy oil and bitumen reservoirs [12]. This section outlines the principles of thermal EOR and explains how renewable energy sources solar and geothermal can fulfill the substantial heat requirements of these processes.

2.1. Overview of Thermal EOR Processes

Thermal EOR primarily involves injecting heat into the reservoir to lower oil viscosity and enhance flow toward production wells [2]. The main thermal techniques include: Steam Flooding: Continuous injection of steam to maintain reservoir pressure and displace oil [13]. Cyclic Steam Stimulation (CSS): Alternating cycles of steam injection, soaking, and production in the same well [14]. In-Situ Combustion: Ignition of a portion of the reservoir's hydrocarbons to generate heat underground [15]. Among these, steam-based methods (steam flooding and CSS) are the most widely used, particularly in heavy oil fields such as California's San Joaquin Basin and Canada's oil sands. Conventional steam generation relies almost exclusively on natural gas combustion, which results in substantial fuel costs and high CO_2 emissions [16].

2.2. Energy Requirements and Environmental Challenges

Thermal EOR is extremely energy-intensive. For example, generating one barrel of steam typically requires between 0.25–0.3 MMBtu of fuel energy. This translates into: High operational expenditure (OPEX), especially when gas prices are volatile. Significant CO_2 emissions, often exceeding 0.3–0.5 tons of CO_2 per barrel of oil produced through steam-based methods. As operators and regulators focus increasingly on decarbonization, there is growing urgency to find cleaner energy alternatives to conventional steam production [17].

2.3. Rationale for Integrating Renewable Energy

Solar and geothermal energy offer unique advantages to address these challenges; Solar Thermal Energy - Converts direct solar radiation into high-temperature heat using concentrating collectors (parabolic troughs, Fresnel reflectors, heliostats), Can produce steam at temperatures compatible with EOR requirements (200–350 °C), Particularly effective in arid, high-irradiance regions such as the Middle East and North Africa [18]. Geothermal Energy - Provides a continuous source of subsurface heat extracted from geothermal reservoirs, offers baseload thermal energy with minimal intermittency, can utilize mature or depleted oil wells for co-production, reducing drilling costs. Integrating these renewable sources into EOR processes can lower fuel dependency, improve operational sustainability, and contribute to emissions reduction goals [19].

2.4. Conceptual Configurations

Solar and geothermal integration can be implemented through different configurations; Standalone Solar Thermal Systems: Directly connected to once-through steam generators, Hybrid Systems: Combining solar thermal input with auxiliary gas-fired boilers to guarantee consistent steam supply, Geothermal-Only Systems: Using geothermal heat exchangers and fluid circulation systems, Hybrid Solar-Geothermal Systems: Leveraging the strengths of both renewable sources, solar energy during the day and geothermal heat continuously. These configurations are still under development, and their performance depends on factors such as resource availability, reservoir characteristics, and cost considerations. In summary, renewable-powered EOR represents a promising pathway to decarbonize oil recovery processes by replacing fossil-derived heat with clean, sustainable alternatives. The following sections will explore in detail the technologies, field deployments, and operational considerations of solar and geothermal EOR applications.

3. Solar Applications in Enhanced Oil Recovery

Solar thermal energy offers a clean and increasingly cost-effective alternative to fossil fuels for generating the heat required in Enhanced Oil Recovery (EOR). By concentrating sunlight to produce high-temperature steam, solar systems can reduce both operational costs and greenhouse gas emissions associated with traditional steam injection. This section reviews the main technologies, integration approaches, and field experiences of solar-powered EOR [5].

3.1. Solar Thermal Technologies for EOR

Several solar thermal technologies have been adapted for EOR applications, each with unique advantages; Parabolic Trough Collectors - Curved mirrors track the sun and focus radiation onto a receiver tube filled with heat transfer fluid, Well-established and commercially proven in the power sector, Typical steam temperatures: 250–350 °C, compatible with thermal EOR [20]. Linear Fresnel Reflectors - Use multiple flat or gently curved mirrors arranged in rows to direct sunlight onto a fixed receiver, Simpler design and lower construction costs compared to troughs, Suitable for producing medium-temperature steam [21]. Heliostat Fields with Central Receivers (Power Towers) - Arrays of sun-tracking mirrors concentrate light onto a central receiver at the top of a tower. Can reach higher temperatures (>500 °C), though less common in EOR so far. These technologies can be tailored to match specific reservoir and site conditions, such as available land, solar resources, and required steam flow rates [22].

3.2. Integration Approaches in Oilfield Operations

Solar thermal systems can be deployed in various configurations; Standalone Solar Steam Generation - During daylight, solar collectors supply steam directly to injection wells, Effective in regions with consistent high solar irradiance. Hybrid Solar-Gas Systems - Solar steam partially offsets natural gas combustion, Gas-fired boilers supplement steam during periods of low solar output, maintaining continuous injection. Thermal Energy Storage - Storage solutions, such as molten salt tanks or pressurized hot water, smooth fluctuations and extend steam availability into evenings. Hybrid systems are currently the most practical approach, providing reliability while significantly reducing fuel use.

3.3. Field Demonstrations and Case Examples

Several real-world projects have validated the feasibility of solar EOR; Glass Point Solar Mirah Project (Oman) - One of the world's largest solar EOR installations, uses enclosed parabolic troughs inside glasshouses to protect mirrors from dust and wind, Designed capacity: Over 1,000 MW thermal equivalent, Outcome: Significant reductions in natural gas consumption and CO_2 emissions [5]. California Heavy Oil Fields - Smaller pilot systems tested parabolic trough and Fresnel collectors to supply steam in the San Joaquin Valley. Demonstrated the technical viability in mature reservoirs with heavy oil. While still limited in scale globally, these examples show that solar thermal systems can integrate effectively with conventional EOR infrastructure [23].

3.4. Performance and Economic Considerations

Key factors influencing the adoption of solar EOR include; Solar Resource Availability - High direct normal irradiance (DNI) is critical for efficiency. Land Requirements - Collector fields require significant surface area. Capital Costs: Initial investment remains higher than gas boilers, though declining with technology maturation. Fuel Savings: Reduced natural gas consumption can improve long-term economic viability, especially in regions with high gas prices. Lifecycle assessments have shown that solar EOR can substantially cut greenhouse gas emissions per barrel of produced oil. In summary, solar thermal technologies provide a proven, scalable solution to decarbonize EOR operations. The next section will explore geothermal applications as another renewable option for supplying heat in oil recovery.

Table 1 Comparative Analysis of Key Papers on Renewable Energy Integration in Oil Recovery

Reference	Objectives	Results	Findings	Practical Implications
[24]	Present advances in geothermal power systems in oil and gas; highlight challenges and opportunities	Geothermal resources can reduce GHG emissions; abandoned wells lower project costs	Optimizes geothermal development using oil and gas infrastructure; enhances thermally enhanced oil recovery	Lower emissions; repurpose abandoned wells; improve energy efficiency in oil fields
[25]	Investigate integrating renewable energy with thermal energy storage; address limitations	Integration enhances energy efficiency and reduces emissions	Hybrid systems mitigate intermittency, improve reliability	Substitute fossil fuels; improve system resilience; inform design of hybrid EOR systems
[26]	Review hybrid steam-flue gas technology for oil	Improves oil recovery efficiency;	Optimizes thermal processes; reduces environmental impacts	Enhance energy efficiency; lower costs in heavy oil recovery

	recovery; evaluate mechanisms	reduces emissions and costs		
[27]	Review gravity-assisted heat pipes for geothermal extraction; analyze challenges	200 kW thermal power achieved from 3,000m depth; efficiency challenges identified	Safe geothermal extraction; efficiency issues remain	Safer, low-power geothermal extraction; informs heat pipe system development
[28]	Investigate solar-hydrogen hybrid systems for energy efficiency	Annual cost optimized to $57,539; CO_2 emissions down to 0.147 go_2/kWh	80% renewable integration; significant emissions reductions	Reduce operational costs and carbon footprint in oil and gas
[29]	Analyze thermodynamics; optimize design for heating and power	COP improved to 6.5; 180 kW power output; 27.5% thermal efficiency	Hybrid system significantly improves efficiency	Enhance heating/power supply for industrial applications
[10]	Propose and evaluate solar-geothermal hybrid system	Desalinated water: 28.46 kg/s; 21.9% energetic efficiency; payback 4.74 years	Zero-emission hybrid system; high efficiency	Sustainable power, heating, desalination for oil fields
[30]	Assess intermittent extraction for sustainable geothermal	Reservoir lifespan extended by 17.7 years; clean power +13%	Improves geothermal sustainability and output	Prolongs reservoir life; increases clean energy production
[31]	Design and analyze multigeneration system	Generates 1.2 MW electricity; CO_2 cut by 254 kg/h	Integrates electricity, cooling, hydrogen, desalination	Reduce emissions, energy costs for offshore/island oil fields
[32]	Evaluate LSWI fundamentals, lab/field studies, economics	Identifies mechanisms, economic viability, hybrid methods	LSWI improves oil recovery; viable desalination options	Enhance oil recovery efficiency; lower salinity management costs

4. Geothermal Applications in Enhanced Oil Recovery

Geothermal energy represents a steady, renewable source of heat that can be directly utilized for Enhanced Oil Recovery (EOR) processes. Unlike solar energy, which is intermittent, geothermal systems provide baseload thermal energy, offering consistent steam or hot water injection without dependence on weather or daylight [5]. This section reviews geothermal resources, extraction techniques, integration strategies, and practical considerations for geothermal-powered EOR.

4.1. Geothermal Heat Extraction Principles

Geothermal energy originates from the natural heat of the Earth's interior, accessible through subsurface reservoirs. In oil and gas operations, geothermal heat can be extracted in several ways; Direct Use of Geothermal Reservoirs - Wells drilled into naturally hot formations, Hot fluid circulated to the surface and transferred to steam generators or injected directly into reservoirs [33]. Co-production with Oil and Gas - Mature or depleted oil wells often produce significant amounts of hot water, Heat exchangers recover thermal energy before reinjection or disposal [34]. Enhanced Geothermal Systems (EGS) - Artificially created reservoirs using hydraulic stimulation to increase permeability in hot dry rock formations, still experimental but may expand geothermal EOR potential. These approaches can provide reliable heat streams compatible with thermal EOR requirements [33].

4.2. Integration into EOR Operations

Geothermal heat can be incorporated into oil recovery systems in two main ways; Direct Steam Injection - Geothermal fluid flashed into steam and injected into the reservoir, Suitable for reservoirs requiring low to medium-pressure steam. Heat Exchanger Systems - Geothermal fluid heats water in closed-loop exchangers, avoids introducing geothermal brine into oil reservoirs, reducing scaling and corrosion risks. Integration design depends on resource temperature, reservoir properties, and environmental constraints.

4.3. Field Examples and Case Studies

Though geothermal EOR is still relatively rare, several projects demonstrate its potential; California's San Joaquin Valley Operators have utilized co-produced geothermal heat to supplement steam injection, Studies have shown fuel savings and emission reductions compared to gas-fired boilers [35]. In Indonesia and China, Pilot programs have evaluated the feasibility of tapping high-temperature geothermal resources to support heavy oil recovery [36]. Co-production in Mature Fields - Many mature oil fields produce significant geothermal fluids that are often discarded, retrofitting these sites with heat recovery systems can unlock underutilized energy. Overall, field experience confirms the technical feasibility of geothermal integration, although adoption remains limited [34].

4.4. Technical and Economic Considerations

Several factors influence the viability of geothermal EOR; Resource Temperature and Flow Rate - Higher temperatures improve steam production efficiency. Drilling and Infrastructure Costs - New geothermal wells can be capital-intensive, reusing existing oil wells can lower investment barriers. Scaling and Corrosion - Geothermal fluids often contain dissolved minerals that can foul heat exchangers and pipelines, Advanced materials and water treatment can mitigate these challenges. Emissions and Sustainability - Geothermal energy has a low carbon footprint compared to fossil fuels, Lifecycle analyses confirm significant reductions in greenhouse gas emissions per barrel.

4.5. Opportunities and Challenges

Opportunities; Repurposing depleted oil wells for geothermal extraction, Hybrid systems combining geothermal and solar energy., Supporting energy transition goals in oil-producing regions.

Challenges; High up-front capital costs for drilling and infrastructure, Limited data on long-term operational performance, Need for clear regulatory frameworks and incentives. In summary, geothermal energy offers a dependable, renewable solution to reduce fossil fuel dependence in EOR operations. The next section will explore the potential of combining geothermal and solar systems into hybrid configurations to leverage the strengths of both resources.

5. Hybrid solar-geothermal systems

Hybrid solar-geothermal systems combine the strengths of two renewable resources; solar energy's high thermal output during daylight hours and geothermal energy's continuous, steady heat supply. By integrating both sources, oil producers can achieve greater reliability, improve overall system efficiency, and reduce dependence on fossil fuels even further. This section describes hybrid system concepts, operational benefits, and challenges specific to Enhanced Oil Recovery (EOR) [37].

5.1. Concept and System Configurations

A hybrid solar-geothermal EOR system typically uses solar collectors and geothermal wells to feed a shared thermal energy loop or steam generator. Common configurations include; Parallel Heat Input Systems - Solar thermal and geothermal heat are delivered in parallel streams to a central steam generation unit. Operators can adjust the proportion of each input based on solar availability and geothermal flow [38]. Sequential Preheating Systems - Geothermal fluid preheats feedwater. Solar collectors further raise temperatures to produce higher-pressure steam; this approach improves the efficiency of solar collectors by reducing temperature lift requirements [39]. Integrated Thermal Storage - Excess solar heat during peak hours stored in molten salt or hot water tanks, Stored energy used during periods of low solar input to maintain stable steam delivery. These flexible configurations allow operators to tailor system design to site-specific resources and operational needs [40].

5.2. Benefits of Hybrid Systems

Integrating solar and geothermal resources offers several compelling advantages; Enhanced Reliability - Geothermal heat provides continuous baseload energy, Solar thermal adds significant daytime capacity, reducing fuel consumption.

Improved Efficiency - Preheating and storage strategies optimize overall thermal performance, better alignment between energy supply and EOR process demands. Reduced Operational Costs - Less reliance on auxiliary gas-fired boilers, Potential savings on fuel, maintenance, and carbon compliance costs. Lower Emissions - Combined renewable contributions can substantially cut greenhouse gas emissions per barrel of oil produced.

5.3. Example Concepts and Pilot Studies

Although large-scale hybrid solar-geothermal EOR projects are still emerging, feasibility studies and pilot concepts have been explored; California Pilot Studies - Small-scale tests evaluated combining solar collectors with geothermal fluid preheating, Early results demonstrated stable steam output and improved energy efficiency [41]. Middle East Feasibility Assessments - Studies have modeled the integration of parabolic trough solar fields with deep geothermal resources in Oman and Saudi Arabia [42]. Research Proposals - Hybrid system modeling has shown potential for up to 60–80% reductions in natural gas consumption compared to conventional boilers. These early studies highlight promising opportunities but also underscore the need for further demonstration [43].

5.4. Technical and Operational Challenges

Despite their benefits, hybrid systems present unique challenges; System Complexity - Designing integrated thermal loops requires advanced engineering, Control systems must dynamically balance variable solar input with geothermal flow. Capital Investment - Combining two renewable systems can increase upfront costs, financial incentives or carbon credits may be necessary to improve economic feasibility. Material Durability - Exposure to geothermal brines and high-temperature solar fluids can accelerate corrosion and scaling, Advanced materials and protective coatings are often required. Data and Monitoring - Limited field data on long-term performance and reliability, Need for robust monitoring and adaptive control strategies.

5.5. Research and Development Needs

To accelerate adoption, further work is needed in; Pilot demonstrations in different climatic and geological settings, Integrated system modeling and optimization, Lifecycle cost and emissions assessments, Development of modular, scalable hybrid solutions. In summary, hybrid solar-geothermal systems hold significant potential to decarbonize EOR by combining continuous geothermal energy with high-output solar heat. The next section will assess the broader environmental and economic impacts of renewable-powered EOR systems.

6. Environmental and Economic Impacts

Integrating renewable energy into Enhanced Oil Recovery (EOR) offers a compelling opportunity to reduce the environmental footprint and improve the economic sustainability of oil production. This section evaluates the key impacts of solar and geothermal EOR systems, focusing on emissions reduction, resource use, lifecycle costs, and broader sustainability considerations.

6.1. Greenhouse Gas Emissions Reduction

Traditional thermal EOR, especially steam injection, is among the most carbon-intensive oilfield activities due to large quantities of natural gas combusted to produce steam. Renewable-powered EOR can significantly cut these emissions; Estimated Emissions Reductions - Solar EOR projects have demonstrated up to 80% reduction in CO_2 emissions from steam generation during peak solar hours, Hybrid solar-gas configurations can reduce annual emissions by 20–40% depending on solar availability and storage capacity, Geothermal systems provide nearly zero-emission heat, further lowering the carbon intensity of oil production, Lifecycle assessments consistently show that renewable EOR substantially improves the overall emissions profile compared to conventional approaches.

6.2. Water Use and Environmental Footprint

Renewable EOR also offers benefits beyond emissions; Reduced Water Use: Solar thermal systems using closed-loop heat transfer fluids consume less water than wet-cooled natural gas boilers, Minimized Air Pollutants: Fewer nitrogen oxides (NOx), sulfur oxides (SOX), and particulate emissions, Land Use Considerations: Large solar collector fields can impact land availability and ecosystems, requiring careful siting and design, Geothermal Fluid Management: Proper handling of brines is essential to prevent scaling, corrosion, and groundwater contamination. Overall, with appropriate mitigation strategies, renewable systems are environmentally preferable.

6.3. Operational Costs and Fuel Savings

While the upfront capital costs of renewable EOR installations are typically higher, long-term operational savings can be substantial. Cost Benefits include Fuel Savings - Replacing or offsetting natural gas consumption significantly reduces operating expenses, particularly in regions with high fuel prices. Predictable Energy Costs - Solar and geothermal resources provide stable energy costs over decades, insulating operators from fuel price volatility. Maintenance - Fewer moving parts in solar fields can reduce maintenance requirements compared to gas turbines and boilers. Economic feasibility improves in locations with strong solar resources, geothermal availability, or incentives for emissions reduction.

6.4. Capital Investment and Payback Periods

Despite operational advantages, the initial capital costs remain a barrier. These include; Solar Thermal Systems Large collector fields, thermal storage units, and integration infrastructure require significant upfront investment. Geothermal Systems, drilling geothermal wells or retrofitting oil wells involves high initial expenditures. Hybrid Systems - Combining both technologies further increases complexity and cost. Typical Payback Periods - Studies estimate payback periods ranging from 5 to 10 years depending on; Natural gas prices, Solar and geothermal resource quality, Project scale, Availability of subsidies or carbon credits. As technologies mature and economies of scale improve, costs are expected to decline further.

6.5. Sustainability and Policy Alignment

Adopting renewable-powered EOR supports broader environmental and policy objectives; Alignment with Net Zero Targets - Many oil-producing countries and major companies have committed to reducing operational emissions. Carbon Markets and Incentives: Growing carbon pricing mechanisms improve the competitiveness of low-carbon EOR. Sustainability Credentials: Operators can demonstrate leadership in environmental stewardship and innovation. These factors increasingly influence investment decisions, regulatory approvals, and public perception. In summary, renewable EOR systems deliver measurable environmental benefits and can enhance long-term economic resilience. The next section will explore the challenges and barriers that must be addressed to scale up these solutions globally.

7. Challenges and Barriers to Adoption

While renewable-powered Enhanced Oil Recovery (EOR) shows strong potential to decarbonize oil production and improve sustainability, widespread adoption faces several technical, economic, operational, and regulatory challenges. This section outlines the key barriers constraining deployment and highlights areas requiring focused action.

7.1. Technical Integration Challenges

Integrating renewable energy into established oilfield operations is inherently complex; System Compatibility - Conventional EOR infrastructure was designed around gas-fired boilers, retrofitting existing facilities requires careful engineering to align steam quality, flow rates, and pressure with reservoir requirements. Thermal Variability - Solar energy is intermittent, influenced by weather and daylight cycles, even with storage, maintaining steady steam injection remains a challenge for process reliability. Materials and Corrosion - Geothermal fluids often contain high mineral content, accelerating scaling and corrosion in pipelines and heat exchangers. Solar systems exposed to harsh environments (dust, salinity) require durable coatings and cleaning solutions. Operational Expertise - Operating renewable-powered EOR demands new skills in renewable plant maintenance, monitoring, and integration.

7.2. Economic and Financial Barriers

Even when technically feasible, economics can be a major constraint; High Capital Costs - Solar thermal collector fields, geothermal wells, and hybrid storage systems require substantial upfront investment, Operators may hesitate to invest due to oil price volatility and uncertain payback periods. Financing and Risk Perception - Renewable EOR projects are still perceived as higher risk due to limited large-scale precedents, Lenders often prefer proven technologies, creating funding hurdles. Limited Incentives - In many oil-producing regions, subsidies for fossil fuels persist, reducing the cost advantage of renewables, Policy frameworks to reward emissions reductions are often weak or absent.

7.3. Regulatory and Policy Challenges

Policy support is critical but often inconsistent; Permitting and Land Use - Large solar fields can face lengthy permitting processes and competition for land. Geothermal drilling may trigger additional regulatory requirements and environmental assessments. Carbon Accounting - Lack of standardized frameworks to credit operators for emissions reductions achieved by renewable EOR, Uncertainty in how renewable inputs is recognized in sustainability reporting. Market Signals - Weak or absent carbon pricing limits the financial incentive to invest in decarbonization technologies.

7.4. Knowledge and Data Gaps

Limited field experience means there are still many unknowns; Long-term Performance Data - Few case studies document operational performance over multiple years, Reliability and maintenance costs are not yet fully understood. Resource Characterization - Site-specific studies are needed to assess solar irradiance, geothermal reservoir capacity, and integration feasibility. Lifecycle Assessments - More comprehensive evaluations are required to quantify net emissions benefits, water use, and economic impacts across project lifecycles.

7.5. Cultural and Organizational Factors

Adoption of renewable EOR can be slowed by organizational inertia; Conservative Industry Practices - Oil and gas operators often favor familiar, lower-risk technologies, Cultural resistance to innovation can delay trials and pilots. Skill Gaps - Workforce training is needed to operate hybrid renewable systems effectively.

7.6. Summary of Barriers

In combination, these challenges explain why renewable-powered EOR remains limited in scale despite its clear benefits. Overcoming these barriers will require coordinated action from industry, policymakers, researchers, and financiers. The next section outlines future directions and recommendations to accelerate progress.

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8. Future Directions and Recommendations

The integration of solar and geothermal energy into Enhanced Oil Recovery (EOR) is still at an early stage. However, growing environmental pressures and policy commitments to decarbonization are creating momentum to accelerate development. This section highlights key future directions, technological innovations, and strategic recommendations to advance renewable-powered EOR.

8.1. Technological Innovations

Several technological areas have strong potential to improve performance, reduce costs, and increase reliability; Advanced Thermal Storage Systems - Developing cost-effective storage (e.g., molten salt, high-capacity pressurized water) to maintain steady steam injection during low solar periods. Improved Materials and Coatings - Corrosion-resistant alloys and anti-scaling coatings for geothermal fluid handling, Self-cleaning and dust-repellent surfaces for solar mirrors in arid environments. Automated Control Systems - Digital platforms and AI-based controls to optimize hybrid system operation in real time, Predictive maintenance to reduce downtime and extend equipment life. Modular Solar Collector Designs - Prefabricated, scalable collector units that reduce construction time and improve economics for smaller fields.

8.2. Research Priorities

To fill critical knowledge gaps, focused research efforts are needed in the following areas; Resource Mapping - High-resolution assessment of geothermal gradients in mature oilfields, detailed solar resource characterization, including seasonal variability. Integrated Modeling - Coupled reservoir-surface process models to optimize renewable heat input. Lifecycle Assessment - Comprehensive environmental impact studies to quantify emissions, water use, and land footprint. Economic Analysis - Standardized cost models comparing renewable, hybrid, and conventional steam generation.

8.3. Policy and Market Recommendations

Scaling renewable-powered EOR requires supportive policies and market signals; Incentives and Financing Mechanisms Tax credits, subsidies, or feed-in tariffs to offset initial capital costs, Low-interest financing or public-private partnerships to derisk investments. Carbon Pricing and Emission Standards - Clear carbon pricing frameworks to internalize the environmental benefits of renewable EOR. Standardized Certification - Emissions reduction verification to support sustainability claims and access to carbon markets. Permitting Streamlining - Simplified and transparent permitting processes for renewable EOR infrastructure.

8.4. Capacity Building and Knowledge Sharing

Human capital and institutional support will be vital; Training Programs - Workforce development to equip engineers and operators with skills in solar and geothermal systems. Knowledge Platforms - Industry consortia and open-access databases to share performance data and best practices. Demonstration Projects - High-profile pilots in different geographies to validate concepts and build investor confidence.

8.5. Regional Focus and Emerging Markets

Future growth is likely in regions where renewable resources are abundant and oil production remains important, including; The Middle East (high solar irradiance and heavy oil fields), North Africa, California (existing geothermal resources), Latin America, Parts of Sub-Saharan Africa. Tailored approaches will be needed to match local resource, policy, and economic conditions.

8.6. Summary of Recommendations

To accelerate deployment, the following priorities are recommended: Expand field pilots and demonstration projects, Develop advanced storage and control technologies, create supportive policy incentives and financing tools, Build capacity and disseminate operational data, Align renewable EOR with net-zero commitments and sustainability goals. **In summary**, with targeted innovation and policy support, renewable-powered EOR can evolve from niche applications into a mainstream decarbonization pathway for oil recovery. The final section will conclude by summarizing the key insights of this review.

9. Conclusion

Enhanced Oil Recovery (EOR) remains a critical technology for sustaining oil production from mature and heavy-oil reservoirs worldwide. However, the traditional reliance on fossil fuels especially natural gas combustion for steam generation has created significant challenges in terms of cost, emissions, and sustainability. Integrating renewable energy sources, specifically solar thermal and geothermal resources, offers a promising pathway to reduce the carbon footprint and improve the environmental performance of EOR operations. This review has highlighted the current status, technologies, field experiences, and future prospects of solar- and geothermal-powered EOR systems; Solar thermal technologies such as parabolic trough collectors and linear Fresnel reflectors have been successfully deployed in demonstration projects, proving their ability to produce medium- to high-temperature steam for injection. Geothermal energy provides a continuous, stable heat source that can be harnessed directly or in co-production with oil, reducing dependence on fossil fuels. Hybrid solar-geothermal systems offer the advantages of both resources, combining baseload heat with high daytime output to improve reliability and overall efficiency. Field examples, including the Glass Point Mirah project in Oman and pilot tests in California, demonstrate that renewable EOR is technically feasible and capable of achieving substantial fuel and emissions reductions. Despite clear environmental benefits, adoption faces challenges related to high upfront capital costs, system integration complexity, limited long-term performance data, and policy uncertainty. Looking ahead, realizing the full potential of renewable-powered EOR will require coordinated action; Technological innovation in thermal storage, corrosion-resistant materials, and intelligent control systems. Comprehensive research to improve resource assessments, economic models, and lifecycle impact analyses. Policy and financial incentives to de-risk investments and reward emissions reductions. Capacity building and knowledge sharing to develop skilled workforces and disseminate best practices. By addressing these challenges, renewable EOR systems can become a valuable tool in the broader effort to decarbonize oil and gas operations while maintaining energy security and economic competitiveness. In conclusion, solar and geothermal applications in Enhanced Oil Recovery are underexplored but highly promising areas of research and practice. With sustained innovation and supportive frameworks, they have the potential to transform how oil resources are produced in a carbon-constrained world.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclsoed.

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