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Repurposing Petroleum Reservoirs for the Energy Transition: Integrated Pathways for CO₂ Storage, Hydrogen Systems, and Geothermal Energy

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Abstract **Original Research Article**

The accelerating need for decarbonization, driven by global climate targets, has intensified interest in leveraging existing subsurface assets to support the energy transition. At the same time, a significant number of oil and gas reservoirs are approaching the end of their productive life, raising important questions regarding their decommissioning or potential reuse. Repurposing these reservoirs presents an opportunity to transform legacy petroleum infrastructure into valuable components of low-carbon energy systems. This review synthesizes current knowledge on the reuse of depleted petroleum reservoirs for three key applications: geological storage of carbon dioxide, subsurface hydrogen storage, and geothermal energy production. It critically examines reservoir suitability based on geological and petrophysical characteristics, as well as the technical feasibility of each application. Particular attention is given to storage mechanisms, operational constraints, and the role of existing infrastructure in reducing development costs and timelines. The review also addresses cross-cutting challenges, including reservoir integrity, leakage risks, geochemical interactions, and uncertainties associated with long-term performance. While carbon dioxide storage is relatively mature, hydrogen storage and geothermal applications require further validation at scale. Key research gaps are identified in areas such as coupled process modeling, monitoring technologies, and reservoir-specific performance assessment. Overall, repurposing petroleum reservoirs offers a pragmatic pathway to support net-zero objectives by integrating carbon management, energy storage, and renewable energy production within existing subsurface systems.

Keywords: Carbon capture and storage (CCS), Hydrogen storage, Geothermal energy, Depleted reservoirs, Energy transition, Subsurface engineering, Reservoir integrity.

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1. Introduction

1.1 Background

The global energy system is undergoing a profound transformation driven by the need to mitigate climate change and reduce greenhouse gas emissions. International frameworks and scientific assessments have emphasized the urgency of achieving net-zero emissions within the coming decades(Mujeeb et al., 2025). Reports from organizations such as the Intergovernmental Panel on Climate Change and the International Energy Agency highlight that limiting global warming requires both a rapid expansion of low-carbon energy systems and the decarbonization of existing fossil fuel infrastructure. In parallel, many mature petroleum basins are experiencing declining production rates as reservoirs approach depletion. This convergence of climate imperatives and resource depletion has prompted increased attention toward strategies that can repurpose existing subsurface assets rather than abandon them(Rasool & Moiz Hashmi, 2026).

1.2 Problem Statement

A large number of oil and gas reservoirs worldwide are approaching the end of their productive life. Traditionally, such reservoirs are decommissioned, and associated infrastructure is dismantled at considerable financial cost. Decommissioning activities involve well plugging, removal of surface facilities, and environmental remediation, all of which can impose significant economic burdens on operators and governments. At the same time, abandoning these reservoirs may overlook their potential value as subsurface storage or energy resources. The central challenge, therefore, lies in evaluating whether these reservoirs can be safely and economically repurposed for emerging energy applications rather than being permanently retired.

1.3 Opportunity

Petroleum reservoirs represent well-characterized geological systems with extensive datasets acquired over decades of exploration and production. These datasets include seismic surveys, well logs, core samples, and production histories, which collectively reduce geological uncertainty compared to undeveloped subsurface formations. In addition, existing infrastructure such as wells, pipelines, and processing facilities can potentially be reused or adapted, thereby lowering capital expenditure and shortening project development timelines. The combination of known reservoir properties and available infrastructure creates a compelling opportunity to integrate legacy petroleum assets into the evolving low-carbon energy landscape.

1.4 Aim and Scope

This study presents a narrative review of the potential to repurpose petroleum reservoirs for key energy transition applications. Unlike a systematic review, the objective is to provide a critical and integrative synthesis of current knowledge, highlighting both technological opportunities and associated challenges. The discussion focuses on three principal applications: geological storage of carbon dioxide, subsurface storage of hydrogen, and geothermal energy extraction. These applications have been selected due to their relevance to decarbonization pathways and their compatibility with existing subsurface infrastructure.

1.5 Structure of the Paper

The paper is organized as follows. Section 2 examines petroleum reservoirs as subsurface assets, including their geological characteristics and infrastructure considerations. Subsequent sections evaluate their suitability for carbon dioxide storage, hydrogen storage, and geothermal energy applications. Cross-cutting challenges, integration opportunities, and future research directions are then discussed before concluding with key insights.

2. Petroleum Reservoirs as Subsurface Assets

2.1 Types of Reservoirs

Petroleum reservoirs occur in a variety of geological settings and can broadly be categorized into depleted oil reservoirs, depleted gas reservoirs, and associated aquifer systems. Depleted oil reservoirs typically contain residual hydrocarbons and have undergone significant pressure decline due to production. Gas reservoirs, in contrast, often exhibit simpler fluid systems and may offer different storage characteristics due to gas compressibility. In addition, saline aquifers associated with petroleum systems can provide substantial pore volume and are increasingly considered for storage applications. The diversity of these reservoir types influences their suitability for different repurposing pathways(Askarova et al., 2023).

2.2 Key Reservoir Properties

The performance of any subsurface application depends fundamentally on reservoir properties. Porosity and permeability govern the storage capacity and fluid flow behavior within the formation. High porosity provides greater storage volume, while adequate permeability ensures efficient injectivity and withdrawal. Equally important is the integrity of the caprock, which acts as a sealing layer to prevent fluid migration. Caprock effectiveness is determined by its lithology, thickness, and mechanical strength. Reservoir pressure and temperature conditions also play a critical role, influencing phase behavior, fluid density, and chemical interactions within the subsurface(Poda & Talal, 2025).

2.3 Existing Infrastructure

One of the defining features of petroleum reservoirs is the presence of established infrastructure. Production and injection wells provide direct access to the subsurface, while surface facilities such as separators, compressors, and pipelines support fluid handling and transport. This infrastructure can, in some cases, be modified for alternative uses, thereby reducing the need for new construction. However, the suitability of existing wells and facilities depends on their condition, design specifications, and compatibility with the intended application(Sampaio et al., 2025).

2.4 Advantages of Repurposing

Repurposing petroleum reservoirs offers several potential advantages. The availability of detailed subsurface data reduces exploration risk and enhances confidence in reservoir performance. Reuse of infrastructure can lower capital costs and accelerate project timelines compared to greenfield developments. Furthermore, the established regulatory and operational frameworks in many petroleum-producing regions can facilitate the transition to new subsurface uses. These factors collectively contribute to making repurposing an attractive option within the broader energy transition(Song et al., 2025).

2.5 Limitations

Despite these advantages, several limitations must be carefully considered. Aging infrastructure may require significant refurbishment or replacement to meet safety and operational standards. Data uncertainty can persist, particularly in older fields where historical records may be incomplete or inconsistent. Regulatory frameworks are often not fully adapted to emerging applications such as hydrogen storage or large-scale carbon sequestration, leading to potential delays and uncertainties in project approval. Addressing these limitations is essential for the successful and responsible repurposing of petroleum reservoirs(Shabalov et al., 2021). The integration of multiple energy applications within a single subsurface system is illustrated schematically in Figure 1.

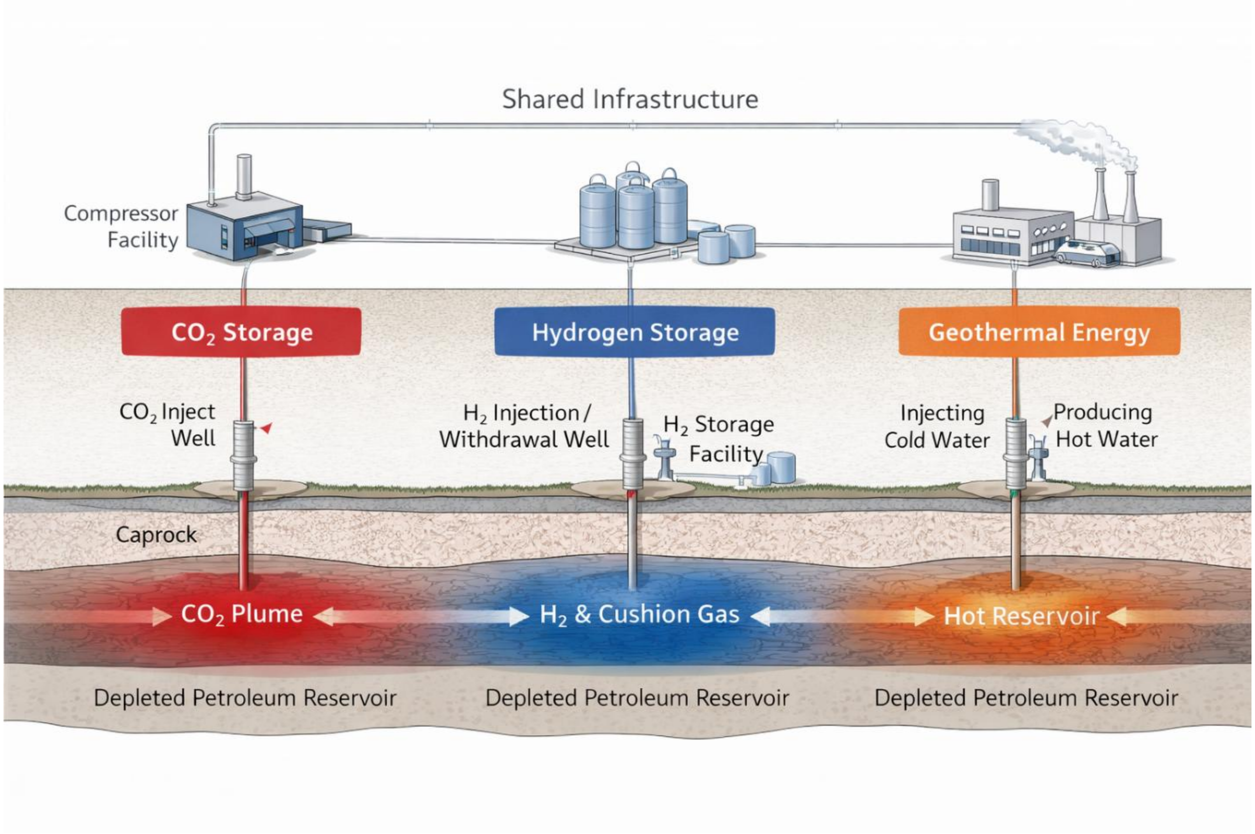

Figure 1. Integrated schematic of repurposed petroleum reservoir applications.

Figure 1. Integrated schematic of repurposed petroleum reservoir applications

Conceptual illustration developed by the authors, showing a depleted petroleum reservoir repurposed for carbon dioxide storage, hydrogen storage, and geothermal energy extraction. The schematic highlights shared infrastructure, reservoir and caprock systems, and key operational processes including CO_2 injection and trapping, hydrogen injection and withdrawal, and geothermal fluid circulation.

3. CO_2 Storage in Depleted Reservoirs

3.1 Overview of Carbon Capture and Storage (CCS)

Carbon capture and storage is widely recognized as an important component of global decarbonization strategies, particularly for sectors that are difficult to electrify such as cement, steel, and certain chemical industries. CCS involves the capture of carbon dioxide from point sources, followed by its transport and long-term storage in geological formations. Among the available storage options, deep saline aquifers and depleted hydrocarbon reservoirs are the most extensively studied. Saline aquifers offer large theoretical storage capacity, but their characterization is often limited. In contrast, depleted petroleum reservoirs benefit from decades of exploration and production data, which can reduce uncertainty and support more reliable storage assessments(Liu et al., 2025).

3.2 Mechanisms of CO_2 Storage

The effectiveness of geological carbon storage depends on several trapping mechanisms that operate over different temporal and spatial scales. Structural trapping occurs when CO_2 accumulates beneath an impermeable caprock, similar to the way hydrocarbons were originally contained. Residual trapping involves the immobilization of CO_2 within pore spaces as disconnected droplets during fluid migration. Solubility trapping takes place when CO_2 dissolves into formation fluids, increasing storage security over time. Mineral trapping, which is typically a slower process, involves the reaction of dissolved CO_2 with minerals to form stable carbonate compounds. The relative contribution of each mechanism depends on reservoir properties, fluid composition, and injection conditions(Rahaman & Islam, 2025).

3.3 Suitability of Petroleum Reservoirs

Depleted petroleum reservoirs are considered suitable candidates for CO_2 storage due to their demonstrated ability to retain buoyant fluids over geological timescales. The presence of an effective caprock provides confidence in long-term containment. As shown in Figure 1, carbon dioxide is injected into the reservoir where it is contained beneath an impermeable caprock. Furthermore, extensive datasets including seismic surveys, well logs, and production histories enable more accurate modeling of reservoir behavior. These factors reduce uncertainty in storage capacity estimates and enhance the predictability of CO_2 plume migration. However, prior production activities may have altered reservoir conditions, which must be carefully evaluated(Bashir et al., 2024).

3.4 Enhanced Oil Recovery (CO_2-EOR)

The injection of CO_2 for enhanced oil recovery represents a transitional pathway that links conventional hydrocarbon production with carbon management objectives. In CO_2-EOR operations, injected carbon dioxide improves oil recovery by reducing viscosity and enhancing displacement efficiency. This process can generate revenue streams that offset the costs of CO_2 capture and injection. However, the net climate benefit of CO_2-EOR depends on the balance between stored CO_2 and emissions associated with additional oil production(Hamed & Shirif, 2026). As a result, there is ongoing debate regarding the role of CO_2-EOR within long-term decarbonization strategies.

3.5 Technical Challenges

Despite its potential, CO_2 storage in depleted reservoirs presents several technical challenges. Leakage risks are a primary concern and may arise from faults, fractures, or improperly abandoned wells. The integrity of the caprock must be maintained under changing pressure conditions associated with injection. Pressure management is particularly important to prevent fracturing of the sealing formation or reactivation of faults. In addition, geochemical interactions between CO_2, formation fluids, and reservoir rocks can alter porosity, permeability, and mechanical properties over time(Oliveira et al., n.d.). Addressing these challenges requires site-specific characterization and robust engineering design.

3.6 Monitoring and Verification

Reliable monitoring and verification are essential to ensure the safety and effectiveness of CO_2 storage projects. Time-lapse seismic surveys are commonly used to track the movement of CO_2 within the reservoir. Well logging techniques provide information on fluid saturation and pressure changes near the wellbore. Surface and satellite-based monitoring methods can detect ground deformation and potential leakage pathways. Together, these approaches form an integrated monitoring framework that supports regulatory compliance and builds public confidence in storage operations(Wang et al., 2018).

3.7 Case Studies

Several large-scale projects demonstrate the feasibility of CO_2 storage in geological formations. The Sleipner project in Norway has been injecting CO_2 into a saline formation since 1996 and is often cited as a benchmark for offshore storage. The Weyburn project in Canada combines CO_2-EOR with long-term storage monitoring and has provided valuable insights into reservoir behavior. The Gorgon project in Australia represents one of the largest integrated CCS developments, although it has also highlighted operational challenges related to injection performance and system reliability. These case studies illustrate both the technical viability and the practical complexities of CO_2 storage(Izadpanahi et al., 2024).

3.8 Critical Analysis

While depleted reservoirs offer promising opportunities for CO_2 storage, several uncertainties remain. Long-term storage performance depends on complex interactions that may evolve over decades or centuries. The scalability of CCS is also constrained by infrastructure requirements, including CO_2 transport networks and suitable storage sites. Public acceptance remains a critical factor, particularly in regions where concerns about leakage and environmental impacts persist. A balanced assessment of these factors is necessary to position CO_2 storage within broader climate mitigation strategies(Yasemi et al., 2023).

4. Hydrogen Storage in Petroleum Reservoirs

4.1 Role of Hydrogen in the Energy Transition

Hydrogen is increasingly viewed as a key energy carrier in low-carbon energy systems, particularly for applications that require high energy density or long-duration storage. Green hydrogen, produced through electrolysis using renewable electricity, offers the potential for near-zero emissions across its lifecycle. In addition to its role as a fuel, hydrogen can support grid stability by storing excess renewable energy and providing flexible supply during periods of high demand. Large-scale storage solutions are therefore essential for enabling a hydrogen-based energy economy(Msweli et al., 2025).

4.2 Subsurface Hydrogen Storage Options

Subsurface storage provides a practical approach for accommodating large volumes of hydrogen. Salt caverns are currently the most mature option, offering high deliverability and well-understood behavior. However, their geographical distribution is limited. Deep saline aquifers and depleted petroleum reservoirs present alternative options with potentially larger storage capacities. Depleted reservoirs are particularly attractive due to their existing infrastructure and established geological characterization, although their suitability for hydrogen storage is still under active investigation(Baru et al., 2025).

4.3 Reservoir Suitability

The suitability of depleted reservoirs for hydrogen storage depends on several operational and geological factors. Cushion gas is required to maintain reservoir pressure and ensure efficient withdrawal, which can influence overall storage efficiency. Pressure cycling associated with repeated injection and withdrawal introduces additional mechanical stresses on the reservoir and well infrastructure. Reservoir heterogeneity, fluid composition, and caprock properties also play a role in determining storage performance. These factors must be evaluated through detailed reservoir modeling and experimental studies. The suitability of depleted reservoirs depends on pressure cycling behavior and the requirement for cushion gas to maintain operational stability. Reservoir heterogeneity and fluid interactions also influence storage performance(Okere et al., 2024; Poda & Talal, 2025). Figure 1 also illustrates the cyclic injection and withdrawal of hydrogen within the reservoir system.

4.4 Key Technical Challenges

Hydrogen storage in porous media presents unique challenges compared to natural gas storage. Hydrogen molecules are small and highly mobile, which increases the risk of diffusion and leakage. Loss mechanisms may include microbial consumption and chemical reactions with reservoir minerals or fluids. Material compatibility is another concern, as hydrogen can cause embrittlement in certain metals used in well construction and surface facilities. These challenges necessitate careful material selection and system design to ensure operational safety and efficiency(Ebrahimi et al., 2025).

4.5 Geochemical and Microbial Interactions

Subsurface environments can host microbial communities that interact with injected hydrogen. Sulfate-reducing bacteria may consume hydrogen and produce hydrogen sulfide, which can affect gas quality and pose corrosion risks. Methanogenic microorganisms can convert hydrogen and carbon dioxide into methane, altering the composition of stored gas. Geochemical reactions between hydrogen, formation water, and minerals may also influence reservoir properties. Understanding these interactions is critical for predicting long-term storage behavior(Katz, 2025).

4.6 Operational Considerations

Effective operation of hydrogen storage systems requires careful management of injection and withdrawal cycles. Rapid cycling can impose mechanical stresses on both the reservoir and well infrastructure, potentially affecting integrity over time. Well design must account for hydrogen-specific risks, including leakage and material degradation. Surface facilities must also be adapted to handle hydrogen safely, considering its flammability and low ignition energy. Operational strategies should therefore integrate subsurface and surface considerations(Zeng et al., 2023).

4.7 Case Studies and Pilot Projects

Hydrogen storage in depleted reservoirs is currently at a pilot and demonstration stage. The HyStock project in the Netherlands is exploring underground hydrogen storage as part of a broader energy transition initiative. Additional pilot projects across Europe are investigating the technical feasibility of storing hydrogen in porous media. These efforts are contributing to an improved understanding of reservoir behavior, operational challenges, and system integration(Tarkowski & Uliasz-Misiak, 2025).

4.8 Research Gaps

Significant research gaps remain in the field of subsurface hydrogen storage. Long-term behavior under repeated cycling conditions is not yet fully understood, particularly with respect to microbial activity and geochemical changes. Reservoir-specific performance varies widely, and there is limited empirical data to support large-scale deployment. Further research is needed to develop predictive models, improve monitoring techniques, and establish best practices for safe and efficient operation.

5. Geothermal Energy from Petroleum Reservoirs

5.1 Overview of Geothermal Energy

Geothermal energy represents a reliable and low-carbon energy source capable of providing continuous baseload power. Unlike intermittent renewable sources such as wind and solar, geothermal systems can operate independently of weather conditions, making them an important component of a diversified energy portfolio. Geothermal resources are generally classified into hydrothermal systems, which rely on naturally occurring hot fluids, and enhanced geothermal systems, where permeability is engineered to facilitate fluid circulation. Both approaches aim to extract heat from the subsurface for electricity generation or direct use in heating applications(Dehghani-Sanij et al., 2026).

5.2 Petroleum Reservoirs for Geothermal Use

Petroleum reservoirs offer a promising opportunity for geothermal energy development due to their existing infrastructure and well-characterized geology. Wells drilled for hydrocarbon production can potentially be repurposed for geothermal operations, reducing the need for costly new drilling. In particular, hot sedimentary aquifers associated with petroleum systems provide accessible geothermal resources at moderate depths. These formations often exhibit favorable porosity and permeability, allowing for efficient fluid flow and heat extraction. The availability of seismic and well data further enhances the feasibility of assessing geothermal potential in these reservoirs(Watson et al., 2020).

5.3 Heat Extraction Mechanisms

Heat extraction from petroleum reservoirs typically involves circulating a working fluid through the subsurface to transfer thermal energy to the surface. In open-loop systems, formation fluids are produced, passed through heat exchangers, and reinjected into the reservoir. This approach relies on the natural permeability of the formation and the availability of sufficient fluid volumes. Closed-loop systems, in contrast, circulate fluids within sealed wellbores or pipelines, minimizing direct interaction with the reservoir. While open-loop systems can achieve higher heat extraction rates, closed-loop systems may offer advantages in terms of reduced scaling, corrosion, and environmental impact(Qiao et al., 2024). The selection of an appropriate system depends on reservoir characteristics and operational objectives.

5.4 Technical Challenges

Several technical challenges must be addressed to ensure the long-term viability of geothermal operations in petroleum reservoirs. Thermal decline is a key concern, as continuous heat extraction can reduce reservoir temperature over time, affecting energy output. Scaling and corrosion can occur due to the chemical composition of formation fluids, leading to reduced efficiency and increased maintenance requirements. Flow assurance issues, including changes in fluid properties and potential blockages, can further complicate operations. These challenges necessitate careful reservoir management, material selection, and system design to maintain performance and reliability(Li et al., 2025).

5.5 Economic Considerations

The economic feasibility of geothermal development in petroleum reservoirs is influenced by both cost savings and additional expenditures. The reuse of existing wells and infrastructure can significantly reduce drilling and capital costs, which are typically among the largest expenses in geothermal projects. However, conversion costs associated with modifying wells, installing heat exchange systems, and upgrading surface facilities must be considered. The overall economic viability depends on factors such as resource temperature, flow rates, energy prices, and policy incentives. In many cases, repurposed geothermal systems may offer competitive advantages over conventional geothermal developments(Kassem et al., 2025b).

5.6 Case Studies

Emerging projects demonstrate the potential for geothermal energy production from petroleum reservoirs. In the North Sea, several initiatives are exploring the conversion of depleted oil and gas fields into geothermal energy systems, leveraging offshore infrastructure and existing wells(Santos et al., 2022). In Alberta, Canada, geothermal projects are being developed within sedimentary basins that have a long history of hydrocarbon production(Huang et al., 2024). These projects aim to utilize existing geological knowledge and infrastructure to reduce costs and accelerate deployment. While still in relatively early stages, such case studies provide valuable insights into technical feasibility and economic performance.

5.7 Comparative Advantages

Compared to greenfield geothermal developments, the repurposing of petroleum reservoirs offers several distinct advantages. Reduced drilling requirements lower both financial risk and environmental impact. The availability of extensive subsurface data improves resource assessment and project planning. In addition, existing infrastructure can shorten development timelines and facilitate integration with current energy systems. However, these advantages must be balanced against reservoir-specific limitations, including temperature constraints and infrastructure condition(Souza & Szklo, 2025).

6. Cross-Cutting Challenges and Risks

6.1 Reservoir Integrity

The integrity of the reservoir and associated infrastructure is a critical consideration across all repurposing applications. Wellbores, particularly those that have been in service for extended periods, may present potential leakage pathways if not properly sealed. Degradation of cement and casing materials can compromise containment, especially under changing pressure and temperature conditions(Ibukun et al., 2024). Caprock integrity is equally important, as it provides the primary barrier to fluid migration(Oliveira et al., n.d.). Ensuring long-term containment requires comprehensive assessment and, where necessary, remediation of existing wells and sealing formations. The principal technical challenges associated with reservoir repurposing and their corresponding mitigation strategies are summarized in Table 1.

Table 1. Key challenges and mitigation strategies for repurposed petroleum reservoirs

Challenge	**Affected Application(s)**	**Mitigation Strategy**
Wellbore leakage	CO_2, hydrogen, geothermal	Well integrity assessment, recompletion, improved cementing(Ahammad et al., 2025)
Caprock integrity	CO_2, hydrogen	Pressure management, geomechanical modeling(Poda & Talal, 2025)
Microbial activity	Hydrogen	Reservoir screening, biocide treatment, gas purification(Sampaio et al., 2025)
Scaling and corrosion	Geothermal	Chemical inhibitors, corrosion-resistant materials(Penot et al., 2023)
Induced seismicity	CO_2, geothermal	Controlled injection rates, real-time monitoring(Boyet et al., n.d.)
Data uncertainty	All applications	Advanced reservoir characterization, digital modeling(Aslannezhad et al., 2025)

6.2 Environmental Risks

Repurposing petroleum reservoirs introduces a range of environmental risks that must be carefully managed. Induced seismicity may occur as a result of fluid injection or extraction, particularly in regions with pre-existing faults. Although typically of low magnitude, such events can raise public concern and require monitoring and mitigation strategies. Groundwater contamination is another potential risk, particularly if fluids migrate through compromised wellbores or fractures. Robust site characterization and operational controls are essential to minimize these risks and ensure environmental protection(Hwang et al., 2023).

6.3 Regulatory and Policy Barriers

The regulatory landscape for subsurface energy applications is still evolving. In many jurisdictions, existing regulations were developed for hydrocarbon production and may not fully address the requirements of carbon storage, hydrogen storage, or geothermal energy. The absence of unified frameworks can create uncertainty for project developers and delay implementation. Liability issues, particularly those related to long-term storage and potential environmental impacts, remain a significant concern. Clear regulatory guidelines and well-defined responsibility frameworks are necessary to support large-scale deployment(Raihan, 2025).

6.4 Economic Viability

Economic considerations play a central role in determining the feasibility of reservoir repurposing projects. Capital expenditures include costs associated with infrastructure modification, monitoring systems, and regulatory compliance, while operational expenditures cover maintenance, energy consumption, and personnel. The balance between these costs and potential revenue streams varies across applications. Carbon pricing mechanisms and policy incentives can significantly influence the economic attractiveness of carbon storage projects. Similarly, market demand for hydrogen and geothermal energy will shape investment decisions(Semenova & Churrana, 2025).

6.5 Social Acceptance

Public perception and social acceptance are critical factors in the deployment of subsurface energy technologies. Concerns related to safety, environmental impact, and long-term reliability can influence community support. Transparent communication, stakeholder engagement, and the demonstration of robust monitoring and risk management practices are essential for building trust. Lessons from previous subsurface projects indicate that early and continuous engagement with local communities can improve acceptance and facilitate project development(Tsiaras et al., 2025).

A comparative evaluation of the three primary reservoir repurposing pathways is presented in Table 2, highlighting differences in technological maturity, operational mechanisms, and associated risks.

Table 1. Comparative assessment of repurposing applications in petroleum reservoirs

Parameter	**CO_2 Storage**	**Hydrogen Storage**	**Geothermal Energy**
Primary objective	Emissions reduction and long-term storage	Energy storage and system flexibility	Renewable heat and power generation(Enasel & Dumitrascu, 2025)
Technology maturity	Commercial-scale deployment	Pilot and demonstration stage	Early to mid-stage deployment(Salvador-Carulla et al., 2024)

Storage / recovery mechanism	Structural, residual, solubility, and mineral trapping	Physical storage with cyclic injection and withdrawal	Heat extraction via fluid circulation(Baru et al., 2025)
Key technical risks	Leakage, pressure buildup, caprock integrity	Diffusion losses, microbial consumption, material degradation	Thermal decline, scaling, corrosion(Zeng et al., 2023)
Infrastructure reuse potential	High	Moderate	High
Monitoring requirements	Extensive (seismic, well logging, pressure monitoring)	Developing monitoring frameworks	Moderate monitoring requirements(Fibbi et al., 2022)
Commercial readiness	Established in several regions	Limited large-scale implementation	Increasing but site-dependent (Livet et al., 2022)

7. Integrated and Hybrid Approaches

The evolving role of subsurface systems in the energy transition has led to increasing interest in integrated and hybrid approaches that combine multiple applications within the same geological setting. Rather than treating carbon storage, hydrogen storage, and geothermal energy as isolated solutions, there is growing recognition that their integration can enhance overall efficiency and resource utilization. One example involves the coupling of carbon dioxide storage with geothermal energy extraction. In such systems, injected CO_2 can act as a working fluid for heat extraction due to its favorable thermophysical properties, potentially improving heat recovery while simultaneously achieving long-term storage(Liu et al., 2025).

Similarly, hydrogen storage can be integrated with existing carbon capture and storage infrastructure. Shared use of wells, pipelines, and monitoring systems may reduce costs and accelerate deployment. This approach also supports flexible energy systems in which hydrogen serves as a storage medium for renewable energy, while carbon storage mitigates emissions from residual fossil fuel use(Mansir et al., 2026).

These developments contribute to the broader concept of subsurface energy hubs, where multiple energy functions are co-located and interconnected. Such hubs can facilitate the transition from linear resource extraction models to more circular systems that emphasize reuse, storage, and energy recovery. Circular subsurface energy systems aim to maximize the value of geological formations over their lifecycle, reducing waste and minimizing environmental impact. While still at an early stage of development, integrated approaches offer a pathway toward more efficient and resilient energy systems(Javan et al., 2024).

8. Future Research Directions

8.1 Technical Research Needs

Advancing the repurposing of petroleum reservoirs requires improved understanding of complex subsurface processes. Coupled thermo-hydro-mechanical-chemical modeling is essential for predicting the behavior of reservoirs under changing operational conditions. These models must account for interactions between fluid flow, heat transfer, geomechanical deformation, and geochemical reactions. In addition, long-term monitoring technologies need to be refined to provide reliable data on reservoir performance over extended timeframes. Enhancing the accuracy and resolution of monitoring systems will support risk management and regulatory compliance(Erol, 2025).

8.2 Digital and AI Applications

Digital technologies are expected to play an increasingly important role in subsurface energy systems. Advanced reservoir simulation tools can integrate large datasets to improve predictions of fluid behavior and storage performance. Machine learning and predictive analytics offer opportunities to identify patterns in operational data, optimize injection and production strategies, and detect anomalies that may indicate potential risks. The integration of digital tools with real-time monitoring systems can enable more adaptive and efficient reservoir management(Samnioti & Gaganis, 2023).

8.3 Policy and Market Development

The successful deployment of repurposed reservoirs depends not only on technical feasibility but also on supportive policy and market conditions. Incentives for repurposing existing infrastructure can encourage investment and reduce financial barriers. Carbon pricing mechanisms, emissions trading systems, and subsidies for low-carbon technologies can enhance the economic attractiveness of carbon storage and related applications. Clear regulatory frameworks that address long-term liability and environmental protection are also essential for building investor confidence(Raihan, 2025).

8.4 Interdisciplinary Approaches

The complexity of subsurface energy systems necessitates collaboration across multiple disciplines. Petroleum engineering expertise must be integrated with knowledge from geothermal engineering, environmental science, geochemistry, and energy systems analysis. Such interdisciplinary approaches can facilitate the development of innovative solutions that address both technical and societal challenges. Education and training programs that reflect this integration will be important for preparing the next generation of professionals in the energy sector(Kassem et al., 2025a).

9. Conclusions

This review has examined the potential for repurposing petroleum reservoirs as part of the global energy transition, with a focus on carbon dioxide storage, hydrogen storage, and geothermal energy applications. Each of these pathways offers distinct advantages, supported by the availability of existing infrastructure and extensive subsurface data. Carbon storage is currently the most mature application, with demonstrated large-scale projects and established monitoring practices. Hydrogen storage presents significant potential for energy system flexibility, although technical uncertainties remain. Geothermal energy offers a reliable renewable option, particularly where reservoir temperatures and flow conditions are favorable.

A comparative assessment indicates that no single application provides a universal solution. Instead, the suitability of each approach depends on site-specific geological, technical, and economic factors. Integrated and hybrid systems may offer additional value by combining multiple functions within the same reservoir.

Repurposing petroleum reservoirs can play a meaningful role in accelerating the transition to low-carbon energy systems by reducing costs, leveraging existing assets, and enabling new forms of energy storage and production. It represents a strategic opportunity to transform legacy infrastructure into a resource for sustainable development. In this context, repurposing petroleum reservoirs is not optional but a necessary component of pathways toward achieving net-zero emissions.

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