

Article

Circular Transformation in the Oil and Gas Industry: Impacts on Sustainable Development Goals

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Abstract

A transition to sustainable development and circular economy (CE) principles requires an interdisciplinary understanding of industry-specific technological characteristics and a strategic rethinking of priorities. Given the oil and gas industry's critical role in socio-economic development, tightening environmental regulations, growing resource consumption, waste generation, and environmental impacts, the aim of this research is to identify industry-specific directions for implementing CE principles and to assess their contribution to achieving the Sustainable Development Goals (SDGs). A multi-stage methodology was applied, including an expert evaluation for the identification of key directions for CE implementation; a literature review of related technological practices; subsequent analysis of linkages between each of 12 identified directions and CE principles within the "10R" circularity framework; and qualitative analysis and systematization of their contribution and potential impact on relevant SDGs. Based on these findings, foundational management principles for the oil and gas industry, aligned with sustainability priorities and the circular transition, were formulated. The results obtained provide a methodological basis for strategic management and corporate planning that integrates CE principles and SDGs, which can be further developed to obtain quantitative instruments for assessing the compliance of the companies with CE principles and can be used to improve the sustainability reporting procedure in the oil and gas enterprises. The findings can also be applied to support the modernization of industry standards and justify government support measures.

Keywords: oil and gas industry; energy resources; circular economy; sustainable development goals; technological opportunities for the transition to a circular economy; resource potential; industry management principles



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1. Introduction

The rapid escalation of resource scarcity and deterioration of their quality, driven by rising consumption in recent decades, alongside the aggravation of associated environmental challenges, poses a threat to the existence of modern civilization. This is driving a fundamental shift in the economic paradigm, increasingly dominated by the basic principles formulated within the frameworks of sustainable development and the CE, whose content is continuously being improved [1–3].

The fuel and energy complex (FEC) and all its branches (extraction and processing of different types of fuel resources, power generation, transportation, distribution, and consumption of primary and converted energy carriers) play a crucial role in the economic structure, ensuring the successful operation of all other industries. Given the current structure of the energy resource use and technological baselines, the environmental impact

of the energy sector and its contribution to the problem of resource depletion remain very significant.

Absolutely zero-waste production is theoretically impossible due to limitations of material reusability and the fundamental impossibility of reusing energy. However, for every industry, considering its specific characteristics, including FEC and its different subsectors, the principles of the CE can be adapted and implemented at the level of individual technological processes and incorporated into business strategies, ensuring sustainable enterprise development [4,5]. An analysis of energy policy directions focused on various scenarios and their components, conducted in [6], demonstrated that one of the most relevant scenarios under current conditions is the one focused on environmental sustainability and the CE.

Although industries related to the extraction and use of fossil fuels are linear in the traditional sense, their operations can incorporate technological solutions and practices aligned with CE principles to reduce resource consumption and mitigate environmental impact. To date, methodological issues surrounding the sectoral application of CE principles remain insufficiently explored [7]. For FEC industries specifically, there is a need to identify opportunities for implementing these principles at the enterprise level and to conduct research aimed at improving corporate and project management that would link these opportunities to factors affecting sustainable development.

Formulating CE-aligned business models and development strategies for enterprises, individual industrial sectors, and FEC as a whole must be based on knowledge of relevant industry practices and consideration of national priorities [8].

At the current stage of Russia's economic development, the oil and gas industry provides the foundation for resource and energy security, serves as a major driver of technological innovation, and supports socio-economic progress. Technological transformations within the sector, both in Russia and globally, transform its long-term strategy and generate socio-economic impacts at local and global scales [9].

The use of oil and gas as energy resources entails the generation and accumulation of significant waste volumes, including oil-containing wastes. Refining processes produce large volumes of wastewater, deactivated catalysts, and spent lubricants. Considerable environmental impacts are also associated with oil and gas extraction, the associated petroleum gas (APG) flaring, and carbon dioxide emissions. Meanwhile, from the CE perspective, all waste streams generated in the oil and gas sector can be considered as valuable secondary feedstock. Table 1 summarizes the main types of waste generated in the production processes of the oil and gas industry, categorized by the operational stage.

The application of the CE principles in the oil and gas industry poses a significant challenge to the traditional industry paradigm, yet it also offers a potential source of additional income for enterprises, enhanced competitiveness, and sustainability in the face of stricter environmental regulations, while optimizing resource consumption and reducing ecological pressure. The question of how the oil and gas industry influences progress towards SDGs remains an active subject of scholarly discussion and research. In [13,14], the authors provided an overview and analysis of sustainability reports published by the oil and gas companies in Latin America and Russia, respectively, for the identification of companies' contributions to the achievement of SDGs. Sustainability management strategies and green and lean management concepts at the oil and gas enterprises are also widely discussed in the scientific literature [15,16], as well as discrete sustainable technological solutions [17,18]. However, the identification and analysis of the most promising contemporary technologies applicable to the oil and gas industry and related economic sectors, along with an assessment of their contribution to achieving the SDGs, have not been previously addressed in the literature.

Table 1. Waste generated within the production of the oil and gas industry (made by the authors using data from [10–12]).

Production Processes	Main Waste Streams Generated
Well drilling and oil/gas production	Spent drilling fluids; drilling sludge and oil sludge; gas condensate (fugitive leaks), CO ₂ , and CH ₄ fugitive emissions, flaring; produced water contaminated with petroleum products; process wastewater; waste from equipment maintenance
Transportation and storage	Oil sludge; spent oils and lubricants; produced and oil-containing wastewater; products of corrosion and wear of pipelines and equipment; CO ₂ , CH ₄ , and volatile organic compounds (VOCs) (fugitive leaks, evaporation losses)
Oil/petroleum products spill response and remediation	Oil-contaminated soil, ground, water, and vegetation; contaminated sorbents; spent oil-spill booms; collected oil and petroleum products; VOCs.
Oil and gas processing	Oil sludge; spent lubricants; spent adsorbents and catalysts; resin and acid tar; contaminated process wastewater; carbon oxides (CO _x), nitrogen oxides (NO _x), sulfur oxides (SO _x), hydrogen sulfide (H ₂ S), VOCs.

Despite the implementation of sustainable practices by leading enterprises in the oil and gas sector, the industry demonstrates a relatively limited contribution to achieving the SDGs. Furthermore, in some cases, these companies actively impede progress toward the SDGs due to industry-specific constraints. Challenges in adopting sustainable manufacturing practices in all three spheres of sustainability (economic, social, and environmental) in the oil industry are analyzed in [19]. Integrating CE principles and sustainability practices within the oil and gas industry necessitates the reconfiguration of existing production processes and the adoption of conceptually novel technological solutions. Such transitions demand substantial capital investments and, in many instances, the comprehensive modernization of existing infrastructure [15]. Obstacles to CE implementation in the oil and gas industry are presented in [20].

The International Petroleum Industry Environmental Conservation Association (IP-IECA) has examined opportunities for oil and gas companies to contribute to each of the SDGs [21] and has explored indicators for measuring the sector's transition towards a CE [22]. Currently, the majority of existing research focuses on isolated or specific sustainable pathways and/or technologies within the sector (e.g., supply chain management [23], technology-driven sustainable business models [24], waste management practices [18], produced water treatment [25], etc.). The same applies to CE practices in the oil and gas sector: most studies assess the individual CE practices, technological solutions, and management approaches in terms of sustainability [26] and achievement of the SDGs [27]. To date, however, the research gap remains: the systemic linkages between specific CE principles' implementation pathways in the oil and gas industry and their contributions to SDGs achievement have not been comprehensively studied.

The present research, based on the interdisciplinary approach, aims to solve the following research questions:

RQ1: What are the key industry-specific directions and technological solutions for implementing CE principles in the oil and gas industry?

RQ2: How are these key directions connected with “10R” CE principles?

RQ3: How does each identified direction contribute to SDGs, and what is the character of this contribution?

RQ4: What are the core management principles for oil and gas companies and projects, in context of transition to a CE and sustainable development priorities?

Due to the global energy transition, the growing adoption of CE principles, and the increasing recognition of natural resource and environmental constraints, a comprehen-

sive reconceptualization of the role of the oil and gas industry is urgently needed. This imperative defines the purpose and objectives of this study: (1) to analyze possibilities for applying CE principles; (2) to identify relevant practices and technologies in the production activities of the oil and gas industry; (3) to assess their contribution to advancing the SDGs and define the core management principles for the oil and gas enterprises.

To answer the research questions and to solve the assigned objectives, the research adopts a multi-stage methodology, combining an expert evaluation (Delphi method) to define key industry-specific CE directions, a literature review of technological practices, and a qualitative systematization of their impacts and determination of the management principles.

The expected contribution of this study is as follows. Theoretically, it developed a methodological foundation for qualitatively assessing the compliance of the oil and gas companies with the CE principles, which is a starting point for further elaboration of a toolkit for quantitative assessment. Practically, it provides a basis for strategic management and corporate planning that integrates CE principles and SDGs. It can also be used to improve sustainability reporting procedures in the oil and gas enterprises and to support the modernization of industry standards and justify government support measures.

The manuscript is structured as follows: Section 2 reviews the literature focused on 12 key directions for implementing CE principles in the oil and gas industry, which were selected through expert evaluation; Section 3 explains the multi-stage research methodology; Section 4 presents and discusses the results of the conducted review and analytical research, including the defined connections between the key directions and CE principles, their contribution to achieving the SDGs, and the core management principles for oil and gas companies and projects, aligned with sustainable development priorities and the transition to the CE; and Section 5 provides the main conclusions of the research.

2. Literature Review: Key Directions for Implementing CE Principles in the Oil and Gas Industry

Based on preliminary expert evaluation (see Section 3), the authors identified 12 key industry-specific directions for CE implementation. This section reviews technologies and practices within these 12 directions.

2.1. APG Utilization

APG flaring in the oil and gas industry causes enormous environmental harm and economic damage due to valuable resource losses. The global volume of APG flaring reached 148 billion m³ in 2023, representing a 7% increase compared to 2022. Eliminating routine APG flaring could prevent annual emissions of at least 381 million tons of CO₂ equivalent and mitigate global economic losses estimated from \$9 to \$48 billion [28]. APG flaring results in the release of more than 250 pollutants into the environment, including hydrogen sulfide, nitrogen and sulfur oxides, toluene, carbonyl sulfide, carbon disulfide, and carcinogens like benzene and benzo(α)pyrene [29]. APG may also contain metals (mercury, arsenic, chromium) and compounds from crude oil and formation water. Their deposition severely damages soil and reduces the productivity of ecosystems in oil production zones.

Russia, the largest contributor to global APG flaring, recorded an 11% volume increase to 28.4 billion m³ in 2023, with a flaring intensity of 7.7 m³/barrel [28]. According to [30] (p. 15), economic losses from the APG flaring in Russia amount to about 250 billion rubles/year.

The prospective solutions for APG utilization are the following:

1. *Reinjection and direct use*: The most technologically developed solutions include reinjection into reservoirs to maintain reservoir pressure and enhance oil recovery [31]

and direct use as fuel for heat and power generation [32], which is particularly feasible for remote, isolated, and hard-to-reach regions (offshore shelf and Arctic basins). Use as fuel for combined heat and power plants (CHPP) provides an energy supply and reduces dependency on external fuel.

2. *Processing*: After fractional processing at the gas-processing plants, APG yields natural gasoline, stable condensate, propane–butane fraction, aromatic hydrocarbons, and other products. Liquefied petroleum gas (LPG) obtained from APG can serve as the most environmentally friendly petroleum-derived motor fuel and as a feedstock for manufacturing products with a variety of chemical compositions and high-octane gasoline components, thus extending the lifecycle of hydrocarbon resources [33–35]. The composition profile of APG enables the production of plastics, synthetic rubber, high-octane fuel additives, aromatic hydrocarbons, hydrogen, and other valuable components and products.

3. *Advanced Conversion*: The emerging technologies include chemical and physical solutions. In particular, the “gas-to-liquids” technology (chemical conversion of APG into liquid fuel) is under intensive development [36,37], although currently constrained by economic factors in some regions. In addition, innovative physical methods, such as beta conversion and microwave radiation [30] (p. 15), enable the conversion of APG into stable synthesis oil, which can be further refined to produce motor fuels, aromatic hydrocarbons, plastics, hydrogen, and other products. This maximizes resource efficiency by transforming low-value gas into high-value products.

Thus, preventing routine flaring and subsequently utilizing APG reduces the loss of a valuable resource and, consequently, the need to develop new fields, while lowering environmental pollution. APG utilization technologies can increase the efficiency of oil recovery from fields, yielding additional fuel, energy, and valuable products.

The technological solutions for APG valorization are systematized in Figure 1.

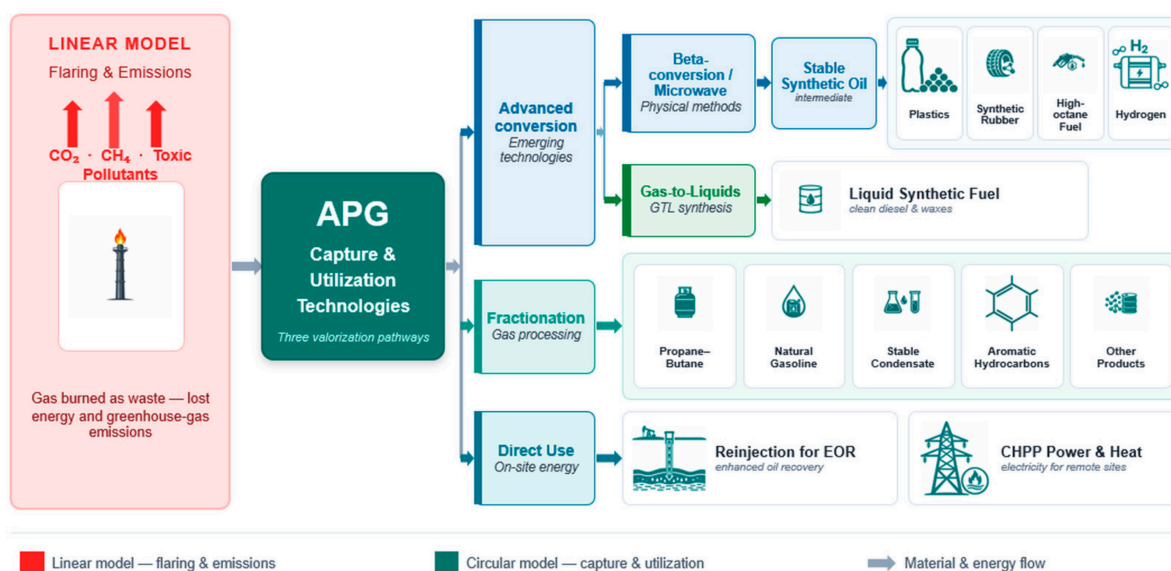


Figure 1. Transition from linear flaring to circular utilization of APG: key technological solutions. The conception and scientific content of the figure were developed by the authors. Microsoft Copilot in Power Point (Microsoft 365, version 2605; office.com) was used for visual layout and graphic design optimization.

2.2. CCUS

The oil and gas sector accounts for approximately 15% of global energy-related emissions [38]. CCUS represents one of the solutions for the oil and gas industry to implement CE principles, through a reduction in emissions and the reuse of oil and gas reservoirs.

1. *Storage and enhanced recovery*: Sequestration/geological storage of CO₂ in onshore depleted or partially oil and gas fields is the cost-effective storage method, especially if existing wells can be repurposed, although their storage capacity is limited. In Russia, the technical potential for CO₂ injection into depleted reservoirs is estimated at 57–157 Gt, while including aquifers raises this potential to over 1000 Gt [39–41]. Currently, the most economically feasible direction is CO₂—enhanced oil recovery (EOR)—which simultaneously increases hydrocarbon extraction and permanently stores carbon [42–47]. Russian companies such as Novatek, Rosneft, Tatneft, and Gazprom Neft are planning to implement CO₂ capture and storage projects. The application of supercritical CO₂ (sc-CO₂) enables maximum efficiency in residual oil recovery due to its unique physicochemical properties; technological challenges associated with the low viscosity of sc-CO₂ are addressed through the addition of viscosity modifiers such as polymers, surfactants, and nanoparticles [48].

2. *Applications in construction and industry*: Beyond the key applications within the oil and gas industry, CO₂ is increasingly used as a raw material. In the construction industry, technologies like CarbonCure, Solidia, Novacerm, and others apply CO₂ in concrete production, contributing both to climate change mitigation and to sustainable development [49]. In petroleum refining, CO₂ can be employed for neutralizing alkaline wastewater: for instance, via SOLVOCARB[®] CO₂ technology that provides a safer and more environmentally compatible alternative to mineral acids by preventing excessive acidification and eliminating corrosion risks [50,51]. Sc-CO₂ is used as a solvent, serving as an environmentally preferable alternative to conventional organic solvents in catalysis, extraction, and fractionation processes, although high-pressure requirements remain a constraint [52]. A promising alternative application is the treatment of drilling waste using sc-CO₂ [53]. In recent years, scientific interest has grown in employing sc-CO₂ as a working fluid in energy storage systems, as well as in the synthesis of materials for batteries, solar cells, and high-energy-density materials. While promising for energy transition, these energy-related technologies require further research to address design challenges, corrosion resistance, and long-term durability and efficiency [54].

3. *Production of chemicals and fuels*: CO₂ can also serve as feedstock for producing methanol, dimethyl ether (DME), synthetic fuels [52,55,56], urea (carbamide) [56,57], and certain polymers (polyurethanes and polycarbonates) [52,56,58]. A promising long-term direction is the production of CO₂-derived synthetic aviation fuel (SAF), which, according to IEA estimates, could supply up to 40% of aviation energy needs by 2050 [59]. However, the economic feasibility of producing SAF from CO₂ depends on the availability of low-cost “green” hydrogen and renewable energy.

4. *Refrigeration and cryogenic carbon capture*: CO₂ can be utilized as refrigerant (R744) [60] in offshore platforms and at floating LNG terminals, which presents a highly environmentally friendly and safe alternative to synthetic refrigerants (zero ozone depletion potential, low global warming potential, non-toxicity, non-flammability, and high energy efficiency in cool climate conditions) [61–63]. Another specialized application is cryogenic carbon capture (Cryogenic CCS), where CO₂ serves simultaneously as the target product and the working fluid. Cryogenic separation technologies (e.g., for LNG cold container cleaning) exploit CO₂ phase transitions to remove it from the gas streams without blocking heat exchangers [64,65].

In the near term, scaling up CO₂-EOR technologies and expanding the use of CO₂ in concrete production offer the most realistic pathway. In the longer term, as catalysis advances and green hydrogen infrastructure develops, priority applications within a CE transition may shift towards CO₂ utilization in petrochemicals for producing synthetic fuels and other high-value-added products.

The technological solutions for CO₂ applications are systematized in Figure 2.

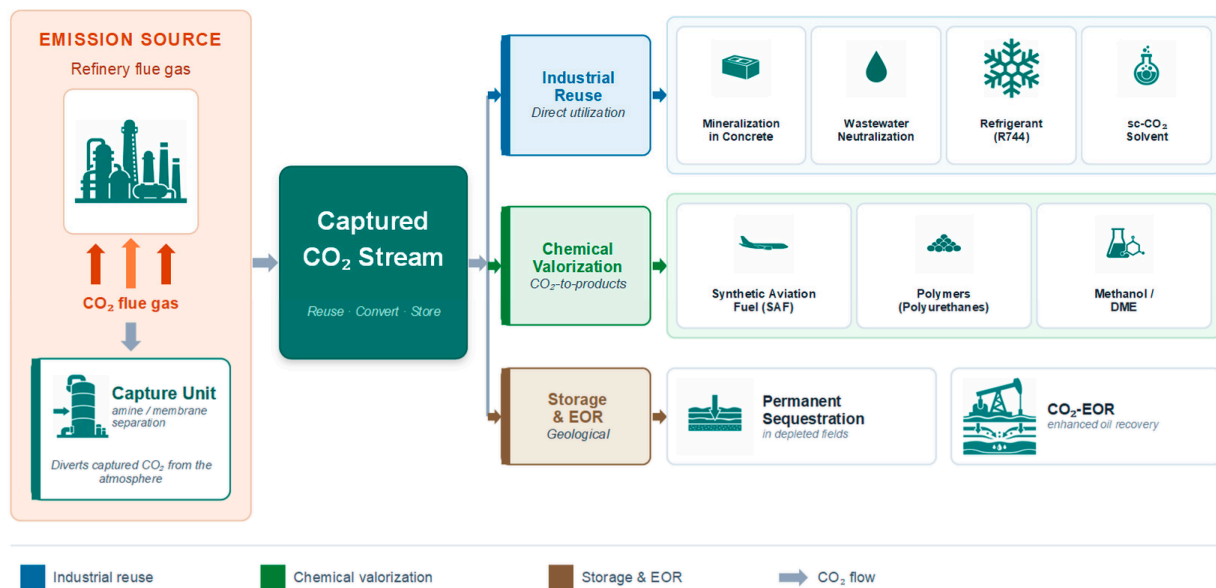


Figure 2. Circular economy directions for CO₂ utilization in the oil and gas industry. The conception and scientific content of the figure were developed by the authors. Microsoft Copilot in Power Point (Microsoft 365, version 2605; office.com) was used for visual layout and graphic design optimization.

2.3. Drilling Sludge and Oil Sludge Management

Drilling and oil sludges, which are the highest-tonnage hazardous and complex waste streams in the oil and gas industry, create significant risks to the environment. Drilling and oil sludges differ in the type of formation mechanisms, composition, and toxicity; these distinctions determine the selection of optimal treatment technologies and opportunities for beneficial utilization [66,67]. In the context of a CE, the objective is a transition from disposal to beneficial utilization of these hazardous wastes, with the objective of obtaining secondary raw materials and energy resources (Figures 3 and 4).

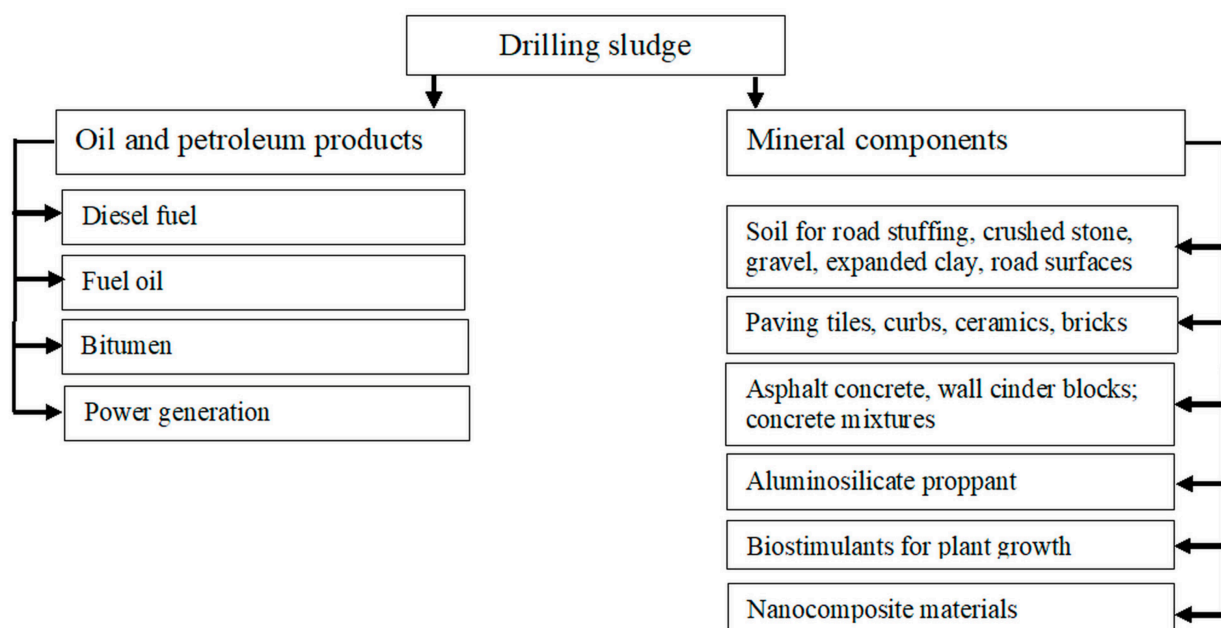


Figure 3. Resource potential of drilling sludge (made by the authors).

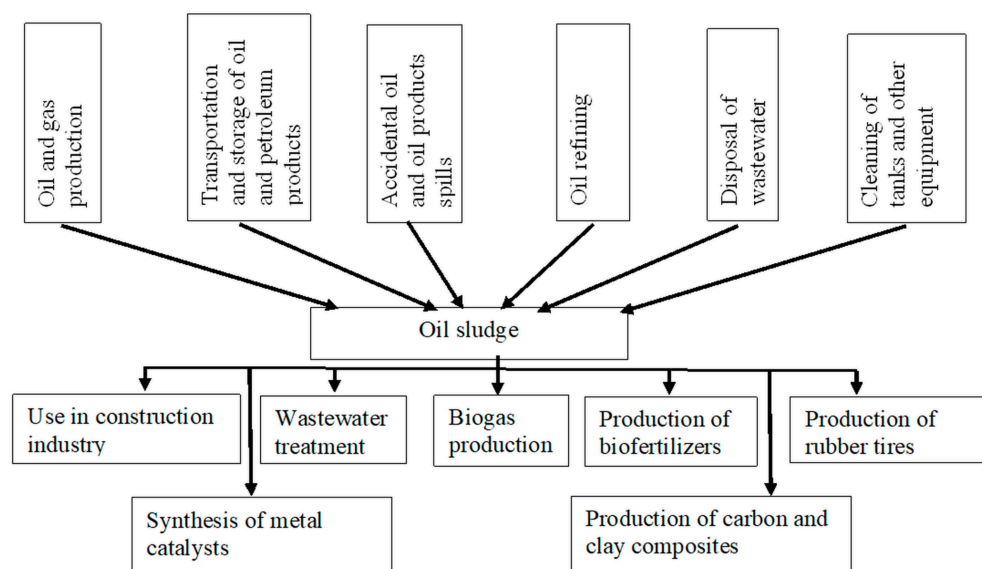


Figure 4. Sources of oil sludge generation and pathways for utilizing its resource potential (made by the authors).

2.3.1. Drilling Sludge Management

Drilling sludge, generated during drilling operations, is a multicomponent mixture, including toxic components (polycyclic aromatic hydrocarbons, salts of barium, heavy metals) and containing a valuable mineral fraction, which is finely dispersed (kaolin, quartz, clay) and recoverable hydrocarbons.

Various methods are employed for drilling sludge utilization, selected in each case based on sludge characteristics: reinjection into formations [67,68]; thermal methods (including incineration, thermomechanical purification and thermal desorption) [68–73]; physical methods (filtration, centrifugation, separation on vibrating screens, vibroacoustic separation), chemical methods (extraction, including sc-CO₂ treatment, solidification); physico-chemical methods [56,74–76]; and biological methods (bioremediation, composting) [68,77].

Mineral Utilization: The dispersed mineral fraction can be used in manufacturing construction materials and products [78–80]. Drilling waste is used for the manufacture of aluminosilicate proppants (for hydraulic fracturing), fill material for road and drilling site construction, paving tiles and curbs, asphalt concrete, wall cinder blocks, concrete mixtures (as aggregate), ceramics, bricks, expanded clay aggregate, crushed stone, gravel, and road surfaces; soil amendments and biostimulants for plant growth [81]. Given the significant content of finely dispersed metals and clay minerals in drilling waste, these materials also find application in producing nanocomposite materials [69,82], which may play an important role in reducing the carbon footprint of the oil and gas industry.

Hydrocarbon Recovery: The liquid fraction extracted from drilling sludge can be processed into diesel fuel and fuel oil, bitumen, or used for power generation, thereby preventing the loss of hydrocarbon resources [81,83].

2.3.2. Oil Sludge Management

Oil sludge is generated during oil and gas extraction, petroleum refining, emergency oil spills, cleaning of tanks and other equipment, wastewater treatment, and maintenance of thermal power plants and tank farms. This type of waste comprises complex physicochemical mixtures of petroleum products, asphaltenes, resins, water, and mechanical impurities (clay, metal oxides, sand) that undergo continuous transformation.

Treatment and recycling employ thermal, chemical, biological, and physicochemical methods, centrifugation-based processing, and other less studied techniques [84,85] along-

side combined approaches [86–91]. Key challenges associated with these treatment and recycling methods include pre-treatment and post-treatment requirements, sensitivity to feedstock composition, reliance on specialized equipment, high consumption of expensive reagents, inapplicability of certain sludge types, high operational costs and low throughput, and risks of secondary pollution. Moreover, no currently available method achieves both environmental safety and economic viability [84].

Supercritical fluid extraction technology (SFE), using propane–butane mixtures or sc-CO₂, is a promising technology, enabling the recovery of up to 96–98 wt. % of dehydrated, mechanically purified petroleum products, water suitable for industrial use, and heavy residue applicable as feedstock for road construction [86,91].

The principal beneficial use pathways for oil sludge, systematized in the review [84], include construction applications, wastewater treatment, biogas production (anaerobic digestion), efficient production of biofertilizers using microorganisms, rubber tire manufacturing, synthesis of metal catalysts, and production of carbon and clay composites for sensors and electronic devices.

By implementing these strategies, the industry can significantly reduce environmental impact and save hydrocarbon resources.

2.4. Enhancing Recovery Rates of Conventional and Unconventional Oil and Gas Reserves

A critical direction for the transition to a CE in the oil and gas industry is the development of hard-to-recover (HTR) reserves. In Russia, HTR reserves account for 53% of oil resources [92] (p. 24) and about 70% of natural gas reserves [92] (p. 43). Enhancing the recovery rate of conventional and unconventional oil and gas reserves, including the extraction of reserves from mature, long-developed fields, represents a central objective that, in our view, aligns with the “reduce” principle of the CE. In this context, “reduce” refers to minimizing extensive resource consumption and improving the resource productivity of hydrocarbon fields. From a CE perspective, increasing the recovery rate should be regarded as a tool for sustainable, lean subsoil use.

Various methods exist for developing fields with HTR reserves: thermal, gas-based, physicochemical, and microbiological [93]. Given the distinct properties of oil and gas and differences in their extraction principles, differentiated strategies are applied to enhance recovery from their respective reservoirs.

Enhanced oil recovery (EOR): Among the EOR technologies applied to intensify oil production are hydrodynamic, physicochemical, thermal, gas-based, and microbiological approaches [94]. The choice of method depends on the specific characteristics of the reservoir and must be technically and economically justified in each case [95]. The application of combined methods can reduce energy consumption and improve overall efficiency (e.g., hydrodynamic–thermal, hydrodynamic–physicochemical, thermal–physicochemical combinations, etc.) [94,96,97]. While hydrodynamic methods (e.g., hydraulic fracturing) remain the most widely used due to their relative simplicity, chemical and thermal EOR methods often face challenges related to high reagent costs, energy intensity, and environmental risks. In a CE context, gas-based EOR methods are particularly promising as they integrate waste utilization with production enhancement as follows:

- CO₂-EOR simultaneously enhances hydrocarbon recovery and achieves an economically beneficial reduction in anthropogenic CO₂ emissions [42,43];
- APG injection methods provide an economically viable pathway for utilizing otherwise flared APG [31].

However, the scale of gas-based method application, particularly CO₂ injection, is currently limited by underdeveloped transport infrastructure for field delivery and the necessity of using expensive corrosion-resistant equipment.

Enhanced gas recovery (EGR): EGR techniques encompass acid treatment (injecting hydrochloric acid solutions of varying concentrations, often thermally enhanced), hydraulic fracturing (in particular, multi-stage multi-section fracturing combined with horizontal drilling), mechanical stimulation (torpedoing) or sampling under vacuum, and CO₂ injection. On gas condensate fields, these methods are specifically designed to improve the co-recovery of both condensate oil and natural gas [98–100]. One promising direction is enhancing oil and gas recovery from shale reservoirs via CO₂ injection [101,102]. Nevertheless, CO₂-EGR methods, like CO₂-EOR, face barriers including the high cost of CO₂ capture and purification systems, risks of diluting produced natural gas, and persistent infrastructure constraints.

By focusing on maximizing extraction from existing fields through advanced EOR/EGR technologies, the oil and gas industry can extend the life cycle of fields, optimize subsoil use, and reduce environmental pressure.

2.5. Treatment and Reuse of Wastewater and Produced Water

The volume of produced water, characterized by very high mineralization and containing a complex mixture of impurities (including organic compounds, suspended solids, and radionuclides [103]), increases due to the rise in the oil and gas production level and the fields' maturation; in wells close to depletion, their total volume can reach 98% of the extracted product [104]. Additionally, oil refineries generate substantial wastewater volumes (0.4 to 1.6 times the volume of crude oil processed), containing complex mixtures of organic and inorganic pollutants in hazardous concentrations [105,106]. In transition to a CE, the aim is to reduce these waste streams and transform them into valuable resources.

Produced water treatment: While partial treatment is sufficient for reinjection into subsurface formation or for use as fracking fluid makeup water, achieving a water quality suitable for safe beneficial reuse (rather than disposal via injection wells) requires integrated multi-stage treatment systems combining membrane filtration, physical, chemical, electrochemical, and biological processes, advanced oxidation processes, heat treatment, and hybrid approaches [103,104,107].

Refinery wastewater treatment: Treatment methods for wastewater generated during oil refining and storage encompass mechanical, adsorption, absorption, physicochemical, chemical, thermal, biological, and other purification methods [106,108–110]. Advanced treatment and reuse technologies not only mitigate environmental impacts but also create an additional water source through recycling, improving crude oil extraction, and reducing losses [111]. Therefore, wastewater treatment facilities should be designed in accordance with CE principles (reduction, reuse, recycling), while employing hybrid approaches that improve the treatment performance without significantly increasing the cost of design and operation.

Post-treatment water streams can be reused in production, while hydrocarbons separated during the treatment process can be directed to refining or value recovery pathways. Heavy organic compounds can serve as a fuel source for heat generation in boilers and furnaces, in household burners, lubricating oil production, or heavy fuel applications (e.g., marine vessels, heavy-duty trucks), or be sent for further processing. Light organic compounds can be valorized as feedstock in the chemical and petrochemical industries to produce various petrochemical products, including solvents and diluents [112,113].

Beneficial reuse pathways for produced water and wastewater from the oil and gas industry include subsurface injection for EOR or formation pressure maintenance, industrial water supply for plant facilities, make-up water for cooling towers, controlled agricultural irrigation, livestock and wildlife watering, and various industrial applications (such as dust control, vehicle washing, make-up water for power plants, firefighting systems) [112–117].

Another significant opportunity is the recovery of valuable components, such as lithium, from produced water [118]. Lithium is a critically important element essential for batteries that underpin the potential of electric vehicle production and the development of solar energy, and virtually all electronic devices with numerous additional applications such as the production of ceramics and raw materials, grease lubricants, powders for molds of continuous casting, use in air purification, medical applications, and more [92] (p. 363). In Russia, lithium has been designated as a strategic resource (order of the Government of the Russian Federation, No. 2473-r, dated 30 August 2022 “On approval of the list of the main types of strategic mineral raw materials”), yet it is currently not recovered from the water produced, despite its potential value [119]. Practical implementation of lithium extraction technologies (feasible at concentrations ≥ 60 mg/L [92] (p. 355)) is a vivid example of the CE principle in action (reuse, recycling for obtaining useful substances); in addition, it could enhance the economic viability of developing difficult-to-recover reserves, diversify projects, and expand the product portfolio of oil and gas companies [120]. Produced waters may also contain other valuable co-produced elements such as bromine, iodine, boron, potassium, magnesium, rubidium, and cesium, that could also be extracted during the development of difficult-to-recover oil and gas reserves for subsequent industrial utilization [120].

By integrating advanced methods of water treatment with resource recovery, the oil and gas industry can significantly reduce consumption of fresh water, mitigate environmental impacts, and create new benefits from waste products.

2.6. Oil-Refining Industry on the Path Towards a CE

The oil refining industry holds considerable potential to implement the CE principles by increasing oil refining depth, improving product quality, processing oil sludges, integrating secondary resources, in particular unsorted organic waste streams, in the composition of feedstock, etc. Implementing these measures maximizes the value derived from crude oil and reduces waste generation, enhances the efficiency of the traditional “linear model”, and facilitates its transition towards greater circularity.

2.6.1. Increasing Crude Oil Refining Depth

In Russia, the average oil refining depth reached 84.9% by 2024 [121]. However, many older refineries still operate with shallow refining schemes, which yield a narrow product slate while requiring a high specific consumption of scarce petroleum feedstock [122,123]. From a CE perspective, transitioning to deep refining corresponds to the “reduce” principle by minimizing the yield of low-value heavy residues (fuel oil, vacuum residue) and scaling up production of high-value outputs such as light petroleum fractions and advanced petrochemical feedstock, which requires a significant expansion of secondary processing capacities [122–126]. Below, the residue-free refining technologies and co-processing of organic waste are discussed.

Residue-free refining technologies: Achieving residue-free oil refining requires advanced secondary processing capacities. Taking into account the limited applications and low demand for solid by-products of deep refining (asphalts), achieving true residue-free oil refining requires advancing fuel-oriented conversion pathways for heavy petroleum residues [122,126]. The possibility of obtaining the maximum amount of motor fuels from crude oil is a fundamental problem of hydrogen balance. For petroleum distillates, it is solved relatively easily; however, for the residue, it becomes very challenging, as heavy residues concentrate sulfur and metals while hydrogen content is minimal. New technological solutions are being developed to overcome these challenges.

One promising approach for residue-free processing of petroleum residues (gudron) via hydrogenation involves new hydroconversion technologies for heavy petroleum feedstock using highly active ultrafine and nanoscale catalysts with enhanced resistance to deactivation [127–132]. Currently, such technologies are at the pilot-scale industrial testing or implementation stage. In particular, the Russian Slurry Hydroconversion process has undergone pilot testing at the TANECO refinery (Nizhnekamsk), demonstrating a pathway towards a CE model.

An alternative strategy entails coking of vacuum residue to remove carbon, with subsequent steam–oxygen gasification of the resulting coke. This integrated processing scheme converts coke into syngas (for methanol or hydrogen production), sulfur, and ash, containing valuable metals (vanadium, nickel), produces electricity, and provides an output of ~85% of high environmental quality motor fuels from the original crude oil. Moreover, the gasoline-to-diesel ratio can be flexibly adjusted by varying the proportion of vacuum gasoil directed to catalytic cracking [9].

Co-processing of organic waste: Along with the problem of enhancing crude oil conversion depth, the oil-refining industry can also address the processing of unsorted organic solid waste (plastic waste, end-of-life tires, etc.) by integrating them into their feedstock streams [133]. Co-processing these wastes with gudron generates liquid products is compatible with fractions of straight distillation of oil (gasoline, diesel fraction, fuel oil), and further co-processing produces commercial petroleum products. This approach is energetically self-sufficient; it yields substantial savings in crude oil consumption, eliminates the need for separate waste recycling facilities, and operates without atmospheric emissions, thereby fully aligning with the CE principles.

The implementation of advanced and residue-free oil refining will require the application of the “rethink” principle of the CE to product consumption patterns, such as the replacement of heavy marine fuel with cleaner diesel fuel in the maritime fleet, justified both by the operational performance and environmental benefits [134].

2.6.2. Processing Heavy Crude Oils and Natural Bitumen

Given the increasing share of unconventional sources in the global hydrocarbon reserves, the processing of heavy crude oils and natural bitumen presents a distinct challenge and opportunity for implementing CE principles. Unlike conventional oil and gas, these feedstocks are characterized by high density and viscosity, low content of light distillate fractions, and elevated concentrations of sulfur, metals, and resinous-asphaltene compounds, which necessitate more intensive pretreatment and advanced technological solutions [135–137].

Production of synthetic crude oil (syncrude): Processing heavy feedstock with its conversion into syncrude, which can be further refined into motor fuels, lubricating oils, and petrochemical products, is an important solution to its beneficial utilization [135,136]. The conversion to syncrude is based on a combination of coking, hydrocracking, hydrotreating, sulfur recovery, and hydrogen production technologies. Alternative processing schemes incorporate visbreaking, de-asphalting, hydrocracking of residues, hydrotreatment of gasoil, and gasification of heavy crude oil [137]. Emerging approaches with the application of ultrafine nanocatalysts in slurry reactors are promising in terms of enhancing conversion efficiency and reducing energy intensity [138–140]. From a CE perspective, this deep conversion minimizes waste generation by maximizing the yield of valuable light fractions from low-quality raw materials.

Resource recovery and construction applications: Heavy crude oils and natural bitumen can be the sources of specific components, such as oxygen-containing organic compounds, vanadium, nickel, and others [141]. Natural bitumen can also be used directly in the

production of asphalt concrete [142] or upgraded into high-quality paving bitumen for road-construction applications.

By application of advanced upgrading technologies, the oil and gas industry can transform heavy residues into strategic resources, improving resource efficiency and reducing waste generation. However, careful management of environmental risks and optimization of energy consumption are required.

2.6.3. Processing Spent Lubricating Oils

The reprocessing of spent lubricating oils is one of the important pathways for implementing CE principles in the oil and gas industry. These wastes contain environmentally harmful components such as metal-bearing additives and organic compounds but also possess significant resource potential [143]. In terms of the CE, the preferred strategy is to maximize the regeneration of spent lubricants into base oils, thereby preventing the loss of valuable resources and returning them to the production–consumption cycle.

Regeneration technologies: Various technologies are employed to restore the properties of the base oil, such as distillation, extraction, chemical treatments, membrane ultrafiltration, adsorption, hydrotreating, pyrolysis, de-asphalting, and others [144–150]. Advanced regeneration processes can produce high-quality base oils that meet modern industry standards. Estimates indicate that a circular model of lubricant recycling, optimized with efficient supply chains, reduces the carbon footprint by 55.35% compared to base oil derived from virgin crude, at significantly lower costs [143].

Alternative valorization pathways: In cases when regeneration into base oil is technically or economically infeasible, other valorization pathways align with CE principles:

- **Energy recovery:** Spent lubricants can be distilled to produce fuel oil, or combusted in cement kilns, industrial boilers, power plants, and cogeneration facilities to generate heat and electricity; they may also be blended with heavy marine fuel for energy recovery [151,152]. Heat and power generation from low-value by-products with sufficient calorific value (low-quality light hydrocarbon gas) is also feasible [143,153].
- **Material reuse:** Residues from reprocessing of spent lubricants can serve as additives in bitumen for road paving applications, extending the lifecycle of materials [153].

By developing regeneration of spent lubricating oils, the oil and gas industry can significantly improve resource efficiency, reduce environmental risks, and dependence on virgin crude oil.

2.6.4. Regeneration and Recycling of Spent Catalysts

The petroleum refining industry is one of the world's major consumers of catalysts essential for the efficiency and selectivity of refining processes [154]. During operation, catalysts undergo deactivation due to coking, poisoning by impurities (sulfur, heavy metals), structural alterations, and mechanical damage [155–157].

Under the traditional linear economy approach, a significant portion of spent catalysts, classified as hazardous industrial waste, is sent to landfills or disposal facilities. This is extremely inefficient as it results in the loss of valuable components (noble and non-ferrous metals). The transition to a CE model focuses on closing the catalyst life cycle through regeneration, repurposing, and metal recovery (Figure 5). The authors see catalyst regeneration and rejuvenation as the oil and gas industry's version of “refurbish” and “remanufacture” principles within this hierarchy.

Regeneration and rejuvenation: The preferred CE strategy is to extend the catalyst's service life. Regeneration processes, such as controlled combustion to remove carbon and sulfur deposits, can restore 75–85% of initial activity [158]. The following rejuvenation stage removes metal ions poisoning the catalytic sites and restores catalytic performance,

sometimes exceeding the activity of fresh samples at a lower cost [159]. For instance, Rosneft Oil Company implements an ex situ regeneration of hydrotreating catalysts, minimizing the need for new catalyst production.

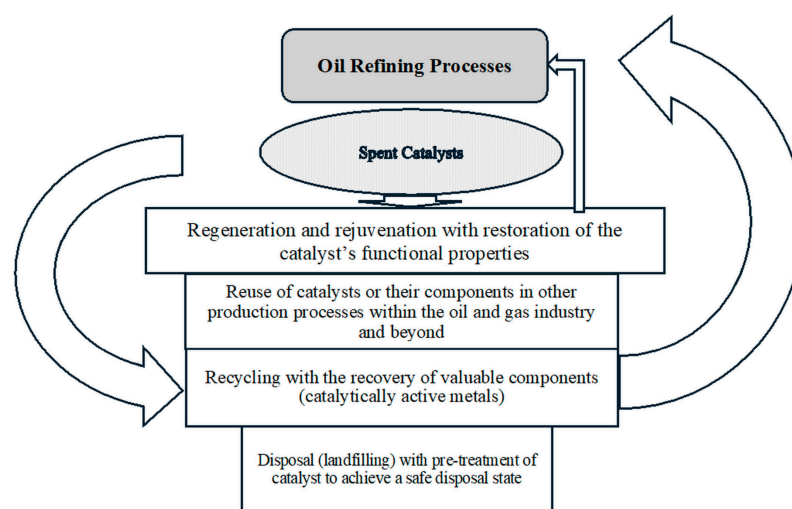


Figure 5. Hierarchy of spent catalysts management in the transition to a CE (made by the authors).

Metal recovery and advanced processing: Where regeneration is technically infeasible or economically unjustified, processing for valuable components is required. The principal methods for processing spent catalysts include (i) hydrometallurgical (based on chemical dissolution of valuable components), (ii) pyrometallurgical (smelting at high temperatures), (iii) pyro-hydrometallurgical (a combination of previous mentioned methods incorporating both high- and low-temperature stages) [160–162]. The hydrometallurgical method offers high selectivity and purity but generates significant wastewater and spent chemicals, while the pyrometallurgical method is suitable for large volumes but energy-intensive and entails significant environmental impact. Pyro-hydrometallurgical is a hybrid approach that compensates for the disadvantages of both methods and represents a more promising strategy for metal recovery [162]. Emerging technologies, such as the use of sc-CO₂ extraction [163], ultrasonic treatment [164], and microwave radiation [162], are promising in terms of increasing the recovery rates (up to 99.9%) and reducing energy consumption. Bioleaching methods using bio- and nanosolvents are also under development [165,166].

Repurposing and alternative use: Spent catalysts, in particular fluid catalytic cracking (FCC) catalysts, can be repurposed in other industries. They can be repurposed in the production of asphalt, cement, and red brick [167], as well as serving as raw material for concrete and mortar manufacturing, partially substituting sand and cement powder [159]. They can also be used as catalysts in the conversion of syngas derived from plastic waste and biomass into synthetic fuels and as feedstock for the zeolite production [159]. Another promising option is their direct use without pretreatment as adsorbents for removing organic dyes from wastewater [168].

It should be noted that *disposal* represents the least desirable option and occupies the lowest hierarchical tier. At this level, detoxification (e.g., calcination to remove sulfur and organic pollutants) can make residual waste safe for landfilling, differing fundamentally from linear economy approaches, where spent catalysts are sent directly to landfills without pretreatment.

By implementing this hierarchical approach, the oil and gas industry can reduce landfill dependency and create economic value from waste streams.

2.7. Reducing Evaporation Losses of Crude Oil and Petroleum Products

Losses from evaporation during the storage and transportation of crude oil and petroleum products are a significant source of resource depletion and air pollution. These losses involve evaporation of toxic low-boiling hydrocarbons, including olefins that contribute to photochemical smog formation, and aromatic compounds, and can be significant. Thus, for gasoline, more than 75% of total losses are attributed to evaporation and reach up to 2% of volume. Notably, evaporation losses from winter-grade gasoline (saturated vapor pressure up to 93 kPa) exceed those from summer-grade gasoline (saturated vapor pressure up to 67 kPa) by more than a factor of two [169]. Evaporation losses are both qualitative and quantitative in nature. In addition to quantitative losses of a valuable resource, evaporation deteriorates product quality because of the volatilization of low-boiling hydrocarbons.

In the context of the transition to the CE, reducing evaporation losses is considered the recovery and reintroduction of a valuable resource back into the cycle, simultaneously delivering both environmental protection and resource-saving benefits. Evaporation losses can be minimized through the following *operational and engineering interventions*:

- *Process optimization*: reducing unnecessary oil pumping within storage depots and ensuring constant sealing of oil transportation system components.
- *Bottom loading*: introduces product beneath the liquid surface, reduces evaporative losses by 30–50% compared to open-stream top filling [169].
- *Vapor recovery units (VRU)*: these technologies include installation of gas pipes that interconnect tanks storing petroleum products of the same grade, enabling the routing of displaced vapor-air mixtures to adjacent tanks rather than venting them to the atmosphere; gas strapping of tanks, gas-equalizing systems of the tank farm; adsorption, condensation, membrane-based, hybrid, and other VRU technologies are also implemented [169–173].

Tank design and passive protection measures involve physical modifications to storage infrastructure that significantly suppress evaporation:

- *Barrier methods*: floating roofs, pontoons, or dynamic floating screens are used that move with the level of stored oil products; these systems approximate a “fully-filled” tank condition, minimizing the volume of vapor-saturated headspace [169,174,175].
- *Thermal regulation*: painting external tank surfaces with light-colored, solar-reflective coatings and installing radiation shields, water spray-cooling systems, or using underground storage can reduce evaporation losses substantially by decreasing temperature fluctuations [169,170]. Evaporation losses in underground tanks are reduced by a factor of 8–10 or more compared to above-ground tanks [169].
- *Inert atmosphere*: introducing nitrogen into the vapor space reduces the partial pressure of light hydrocarbons and prevents oxidative degradation of product quality during storage [176].

Innovative approaches involve introducing micro-quantities of surfactants into petroleum product storage tanks. These compounds concentrate on the liquid–vapor interface, lowering the saturated vapor pressure and significantly reducing evaporation losses without requiring capital expenditure [177–180]. Moreover, this approach exerts a multifunctional positive effect on various oil and gas industry processes (crude oil and gas distillation, natural gas dehydration, and absorption-based gas fractionation), as well as the properties of petroleum products, enhancing vehicle performance characteristics [177,178].

Implementation of these strategies can enable the oil and gas industry to recover evaporated hydrocarbons, reduce environmental pollution, and improve resource efficiency.

2.8. Decommissioning of Production Facilities in Accordance with CE Principles

The decommissioning of oil and gas industry assets is a growing financial and environmental challenge, with global expenditures projected to reach \$104.5–190 billion between 2020 and 2039 [181,182]. From a CE perspective, it must prioritize the maximum feasible reuse of buildings, structures, oil and gas pipelines, equipment, and materials, while facilitating the adaptive repurposing of decommissioned industrial sites for alternative beneficial uses.

Resource recovery and equipment reuse: The main strategy of the CE is to maximize material recovery. Recertification and reuse of equipment, especially high-value assets, can significantly reduce procurement costs and delivery times for replacement equipment [183,184]. Many onshore facilities often represent complex, non-modular structures whose components are difficult to disassemble. For offshore platforms, which are often modular, recycling steel structures is well established, but CE-aligned decommissioning is hindered by remote locations. In addition, both for onshore and offshore facilities, challenges are associated with the limited recycling pathways for certain materials such as composites and concrete [185]. Incorporating CE principles at the design stage—through decommissioning plans, waste management strategies, and modularization of structures—can substantially enhance resource efficiency and minimize waste generation [186].

Repurposing with adaptation: Repurposing of infrastructure may provide significant benefits:

- *Energy purposes:* decommissioned platforms can be converted for offshore wind farms or for hydrogen production.
- *CCUS:* legacy pipelines and reservoirs can be retrofitted for CO₂ transport and storage, which is demonstrated by projects like Quest CCS in Canada [182].
- *Ecological purposes:* decommissioned drilling rigs can be transformed into artificial reefs, improving marine biodiversity (Petronas in Malaysia has repurposed five platforms into artificial reefs) [182].

Site remediation and rehabilitation: From a CE perspective, decommissioning becomes a task of environmental and resource optimization. Various remediation technologies, including bioremediation, are used to rehabilitate hydrocarbon-contaminated sites. For instance, in Russia, successful project examples include land reclamation of disturbed territories in Khanty-Mansiysk Autonomous Okrug and bioremediation of oil-contaminated soils in the Republic of Tatarstan, with significant reductions in soil pollution levels [187].

By transitioning from linear to circular decommissioning and resource management, the oil and gas industry can mitigate environmental impacts, recover economic value, and contribute to the sustainable development of industrial regions.

The comprehensive analysis of current research and industry practices highlights the diversified nature of implementing CE principles in the oil and gas industry. The discussed technological solutions are summarized in Table 2, which provides a basis for the subsequent analysis of interconnections between these directions and global sustainability targets.

Table 2. Summary of key directions and technologies for the circular economy in the oil and gas industry (made by the authors).

Key Direction	Content in the Context of CE	Key Technologies and Practices Identified in the Literature	References
APG utilization	Transformation of associated petroleum gas from waste (flaring) into valuable resources	Reinjection into reservoirs	[31]
		LPG production and fractionation	[33–35]
		Gas-to-liquids (GTL)	[36,37]
		CHPP for autonomous power	[32]
		Beta-conversion to synthetic oil	[30]
CCUS	Capture and storage or beneficial reuse of CO ₂ to close the carbon cycle	CO ₂ -EOR (enhanced oil recovery)	[42–47]
		CO ₂ application in concrete production (CarbonCure, Solidia, Novacerm, etc.)	[49]
		Neutralization of wastewater	[50]
		Production of methanol, DME, and synthetic fuels	[52,55,56,59]
		sc-CO ₂ applications: extraction and solvent use and energy storage systems	[52–54]
		Refrigeration (R744) and cryogenic CCS	[60–65]
Drilling sludge management	Valorization of hazardous drilling waste into secondary raw materials and energy	Reinjection, thermal, physical, physicochemical, and biological methods of utilization	[56,67–77]
		Construction materials (paving tiles and curbs; asphalt concrete, ceramics, brick, etc.)	[78–81]
		Aluminosilicate proppants, biostimulants for plant growth	[81]
		Nanocomposites production	[69,82]
		Hydrocarbon recovery (diesel, fuel oil, bitumen) and power generation	[81,83]
4. Oil sludge management	Processing of complex petroleum waste mixtures for resource recovery	Thermal, chemical, biological, and physicochemical methods; centrifugation-based processing; and combined methods of utilization	[84–90]
		Supercritical fluid extraction (SFE)	[86,91]
		Bioremediation and biofertilizers and biogas production	[84]
		Construction applications, carbon-clay composites, rubber tires, and catalysts	[84]
		Wastewater treatment sorbents	[84]

Table 2. Cont.

Key Direction	Content in the Context of CE	Key Technologies and Practices Identified in the Literature	References
5. Enhanced recovery of conventional and unconventional oil and gas reserves	Maximizing hydrocarbon recovery from existing fields to extend their lifecycle and reduce the need for new greenfield developments	CO ₂ /APG injection for EOR/EGR	[31,42,43,98–100]
		Hydraulic fracturing (multi-stage)	[94]
		Thermal, physicochemical, chemical, gas-based, and microbiological methods	[94–97]
		Shale gas CO ₂ -EGR	[101,102]
6. Treatment and reuse of wastewater and produced water	Purification and reuse of produced water/refinery effluents; extraction of valuable minerals	Membrane filtration; physical, chemical, electrochemical, and biological processes; advanced oxidation processes; heat treatment; and hybrid treatment systems	[103,104,106–110]
		Extraction of lithium, bromine, and other valuable elements	[118–120]
		Water recycling for EOR, industrial water applications, and irrigation	[112–117]
		Hydrocarbon separation and use as fuel, or as a feedstock for petrochemistry	[112,113]
7. Increasing crude oil refining depth	Deep conversion of crude oil to maximize the yield of light fractions and minimize waste generation from heavy residues	Secondary processing	[122–126]
		Slurry hydroconversion (nanocatalysts)	[127–132]
		Coking + steam–oxygen gasification	[9]
		Co-processing with unsorted organic solid waste	[133]
8. Processing heavy crude oils and natural bitumen.	Transforming heavy and unconventional feedstocks into synthetic crude oil and valuable chemical components	Syncrude production (coking/hydrocracking)	[135,136]
		Processing schemes, nanocatalysts in slurry reactors	[137–140]
		Extraction of valuable components	[141]
		Asphalt concrete and paving bitumen	[142]
9. Processing spent lubricating oils	Regeneration of base oils to return valuable resources to the production cycle	Distillation, hydrotreating, membrane ultrafiltration, de-asphalting, and other methods	[144–150]
		Regeneration into base oils	[143]
		Use as fuel, as heat and power generation, and as a bitumen additive	[143,151–153]
10. Regeneration and recycling of spent catalysts	Regeneration, repurposing, and metal recovery	Ex situ regeneration and rejuvenation	[158,159]
		Hydrometallurgy, pyrometallurgy, pyro-hydrometallurgical, and emerging technologies	[160–166]
		Repurposing in construction, alternative catalytic applications, and adsorbents	[159,167,168]

Table 2. Cont.

Key Direction	Content in the Context of CE	Key Technologies and Practices Identified in the Literature	References
11. Reducing evaporation losses of crude oil and petroleum products	Preventing losses of hydrocarbon resources and atmospheric pollution during storage and transport	Process optimization and bottom loading	[169]
		Vapor recovery units (VRU)	[169–173]
		Barrier methods	[169,174,175]
		Thermal regulation and inert atmosphere	[169,170,176]
		Surfactant additives	[177–180]
12. Decommissioning of production facilities in accordance with CE principles	Repurposing of infrastructure and material recovery at end-of-life	Equipment recertification and reuse	[183,184]
		Repurposing of platforms with adaptation (wind farms, hydrogen production, reefs)	[182]
		Repurposing for CO ₂ transport and storage	[182]
		Bioremediation and rehabilitation of sites	[187]

3. Materials and Methods

3.1. Research Design

This study applied a multi-stage methodology including expert evaluation, the literature review, and qualitative analysis. The research is structured in four stages: (1) the identification of key industry-specific CE directions; (2) a comprehensive narrative literature review of technological practices within the CE framework; (3) the decomposition of the relationship between identified directions and CE principles; and (4) a qualitative assessment of contributions to SDGs and determination of principles for management.

3.2. Identification of Key Industry-Specific CE Directions

At this stage, based on extended expert consultations (survey) and the authors' professional experience, a list of key directions for implementing CE principles in the oil and gas industry was compiled for further analysis. "Key industry directions" are understood herein as aggregated groups of technological processes linked to the characteristic properties of hydrocarbon feedstocks, the specificities of oil and gas fields, or the operational characteristics of industry facilities, and possessing the highest potential for improving the efficiency of natural capital use and reducing its losses. Accordingly, the criteria for attribution to key industry directions were the specificity and scale of resources and waste generation, the necessity of applying specialized technologies, and integration into the core production stages of the oil and gas industry (extraction, transportation, processing, decommissioning). General industrial practices (such as separate waste collection, recycling of workwear, use of energy-efficient lighting in offices, etc.), which, while implemented in oil and gas companies, are not sector-specific and are not critical for the industry's transition to a CE, are excluded from this study.

Taking into account that there is no reliable quantitative data related to the potential for implementing circular economy principles within the oil and gas industry, in order to identify key industry-specific CE directions, the authors conducted a three-round anonymous expert survey applying the Delphi method to obtain a consensus-based expert evaluation. The Delphi method is commonly used as a structured, iterative forecasting and decision-making technique to achieve consensus among a panel of experts [188–190]. In the research framework, the method is usually used to determine research priorities, collect and analyze expert opinions on controversial or poorly studied issues, and develop consensus-based scientific theories [188,191].

The expert panel comprised 15 industry practitioners with at least 10 years of professional experience in oil and gas extraction, transportation, and processing, as well as five academic researchers affiliated with universities or research institutes, holding advanced degrees and specialized in energy systems, the oil and gas sector, or CE topics.

In the first round of the survey, experts were asked to address the following questions: (1) Which production processes produce the greatest resource losses? (2) Which waste streams or by-products generated at their enterprise (or elsewhere in the sector) could potentially be used as resources? (3) Are there existing technologies capable of enabling such resource recovery? (4) Are there production development strategies that could reduce resource losses and waste generation in the future? Expert responses from the first round were analyzed to select candidate directions. If a direction was revealed from the responses of at least three experts, it was included in the list. The terminologies used by different experts (e.g., "APG", "associated gas", "flaring gas" reduction) were unified into technological directions. Based on the analysis and integration of the initial expert responses, a preliminary list of 16 directions was compiled:

1. APG utilization.
2. Carbon capture, utilization, and storage (CCUS).

3. Digitalization, automation, and artificial intelligence (AI) application.
4. Drilling sludge management.
5. Oil sludge management.
6. Enhanced recovery of conventional and unconventional oil and gas reserves.
7. Treatment and reuse of wastewater and produced water.
8. Increasing crude oil refining depth.
9. Processing heavy crude oils and natural bitumen.
10. Processing spent lubricating oils.
11. Regeneration and recycling of spent catalysts.
12. Equipment repair and maintenance.
13. Reducing evaporation losses of crude oil and petroleum products.
14. Enhancing equipment reliability and improving its technological performance.
15. Decommissioning of production facilities in accordance with CE principles.
16. Development of corporate culture based on CE and SD values.

At the second round of the survey, the compiled preliminary list of directions was sent back to the experts. The experts were asked to evaluate these directions in terms of (i) technological implementation potential, (ii) alignment with CE principles, (iii) economic and (iv) environmental benefits, and (v) the uniqueness of industry-specific solutions, providing reasoned justification for their assessments (a 5-point Likert scale was applied).

The critical screening criterion for selection to the final stage of the survey was “Industry-specific uniqueness of solutions” with a requirement of a minimal mean score for selection equal to 3.00. Four directions had low mean scores, failed to meet this requirement, and were excluded: “Digitalization, automation, and AI application”; “Equipment repair and maintenance”; “Enhancing equipment reliability and improving its technological performance”, and “Development of corporate culture based on CE and SD values”.

At the second round, experts could propose changes to the classification of the directions based on their comments. Although some experts proposed consolidating sludge management into a single direction, drilling sludge and oil sludge were classified separately because of their fundamentally different physicochemical properties and distinct processing technologies. On the other hand, the treatment and reuse of wastewater and produced water were grouped in a single direction, given the technological commonality of their purification processes and the attribution of water flows as a unified renewable resource that should be reintegrated into the production cycle.

The authors calculated Kendall’s coefficients of concordance separately for all five criteria. The values obtained varied from $W = 0.587$ (technological implementation potential) to $W = 0.757$ (the uniqueness of industry-specific solutions). The significance of the concordance coefficients was established using Pearson’s chi-squared test; the calculated χ^2 values (taking into account tied ranks) were significantly greater than the table values for all criteria ($\chi^2_{crit} = 37.70$, $df = 15$; $p < 0.001$), thus confirming that the consistency of the experts’ opinions was not random, although there were some differences in opinions between the practitioners and academic researchers for several directions (related to economic aspects and technological readiness). The results of the expert consensus evaluation are summarized in Table 3.

At the final round of the Delphi survey, the finalized list of the 12 key directions was distributed to the experts, and a consensus was reached regarding their number and terminological precision. At this stage, experts must confirm the industry-specific character of each direction. The possible responses were: “yes, applicable” (1) or “no, not applicable” (0). All 12 directions selected after the second round received between 95% and 100% approval. The agreement between experts was checked through Cochran’s Q test. The

calculated $Q = 10.00$ ($df = 11$, $p = 0.530 > 0.05$) indicated that there were no significant differences in expert evaluations, and a consensus was obtained.

Table 3. Statistical analysis of expert assessment agreement (20 experts) (made by the authors).

Evaluation Criteria	Kendall's Coefficients of Concordance (W)
1. Technological implementation potential	0.587
2. Alignment with CE principles	0.665
3. Economic benefits	0.669
4. Environmental benefits	0.753
5. The uniqueness of industry-specific solutions	0.757

The analysis of the third round yielded the following key industry directions for implementing CE principles:

1. APG utilization.
2. Carbon capture, utilization, and storage (CCUS).
3. Drilling sludge management.
4. Oil sludge management.
5. Enhanced recovery of conventional and unconventional oil and gas reserves.
6. Treatment and reuse of wastewater and produced water.
7. Increasing crude oil refining depth.
8. Processing heavy crude oils and natural bitumen.
9. Processing spent lubricating oils.
10. Regeneration and recycling of spent catalysts.
11. Reducing evaporation losses of crude oil and petroleum products.
12. Decommissioning of production facilities in accordance with CE principles.

3.3. Literature Review of Technological Practices Within the CE Framework and Decomposition of Their Connections with the CE Principles

In the second stage of the study, a traditional or narrative literature review and an analysis of specific technological opportunities within the 12 selected directions were conducted in the context of CE principles and levels of circularity of the 10R framework [3]. The traditional narrative literature review provides a broader overview of a topic; it relies on various flexible search methods and the researcher's expertise and prior knowledge [192,193]. The stages, structure, and approaches to the article selection could vary in the narrative review; the most common framework is presented in [194].

The literature review included the following stages: (1) literature search and primary screening; (2) secondary screening in accordance with eligibility criteria; (3) analysis and synthesis of the information that has been gathered; and (4) writing and preparation of the review.

The literature search was conducted in the period from June to December 2025. The primary information base included the Scopus and Science Direct databases, supplemented by Google Scholar-indexed publications, analytical reports, and statistical reviews, which were directly related to technological solutions and practices of the oil and gas industry within the context of CE implementation. Short abstracts of conferences and non-indexed literature were excluded from the information base for further research. A comprehensive literature search was conducted across the abovementioned databases for each direction separately using composite search strings that combined relevant keywords for each established direction to identify the pertinent literature. For example, for the APG direction, the authors applied search queries such as ("associated petroleum gas" OR "APG") AND ("cir-

cular economy" OR "CE"); ("associated petroleum gas utilization" OR "APG utilization"); ("associated petroleum gas" OR "APG") AND ("enhanced oil recovery" OR "EOR") and so forth. For CCUS the search queries were queries such as ("Carbon Capture, Utilization and Storage" OR "CCUS") AND ("oil and gas industry"); ("Carbon Capture, Utilization and Storage" OR "CCUS") AND ("enhanced oil recovery" OR "EOR"); ("Carbon Capture, Utilization and Storage" OR "CCUS") AND ("refrigeration" OR "R744"), and so forth. The same approach was applied to each of 12 selected directions.

The selection of keywords was grounded in a preliminary analysis of prior studies, supplemented by the researchers' subject-matter expertise in the industry. A lower time-frame was not specified, to avoid missing technologies, important in the context of this study; however, recent studies published between 2010 and 2025 were prioritized to focus on cutting-edge technologies in the oil and gas industry.

The authors manually screened titles, abstracts, keywords, and highlights (where applicable) to select the most relevant articles and reviews. The shortlisted articles underwent manual full-text screening to confirm their eligibility and the relevance of the described technologies. Selection criteria also included the publication date, document type, journal, citation count, theoretical/practical viewpoints, and the inclusion of case studies. A subset of these sources was further examined to identify additional references.

On this basis, the third research stage involved a conceptual decomposition of the linkages between each direction and CE principles.

3.4. Qualitative Assessment and Systematization of the Impacts

In the fourth research stage, a qualitative analysis and systematization were performed to assess the contribution and nature of the impact of each identified direction on the relevant SDGs. Furthermore, fundamental management principles for the oil and gas industry were formulated, integrating sustainability priorities and the transition to a CE.

4. Results and Discussion

4.1. Application of CE Principles in the Oil and Gas Industry

The implementation of CE principles in the oil and gas industry aims to maximize the reintegration of by-products into production cycles, reduce waste generation, and extend the service life and efficiency of resources and infrastructure.

The primary focus of the analyzed key directions 1–4, 6, and 9–11 is on a core aspect of the CE: the management of solid, liquid, or gaseous waste streams through their reuse or recycling. Directions 5, 7, and 8 are associated with enhancing feedstock utilization efficiency and minimizing overall resource losses. Direction 12 ensures the responsible closure of material use cycles and the rehabilitation of affected territories. Notably, each of these directions contributes to the implementation of multiple CE principles simultaneously.

Table 4 systematizes the results of the conducted review and analytical research on the interlinkages between the 12 key directions and CE principles.

Half of these directions—(1) APG utilization, (2) CCUS, (3) drilling sludge management, (4) oil sludge management, (6) treatment and reuse of wastewater and produced water, and (10) regeneration and recycling of spent catalyst—contribute to the implementation of four CE principles: reduce, reuse, recycle, and recover. Direction 6 additionally contributes to the repurpose principle, while Direction 10 advances the repurpose, refurbish, and remanufacture principles.

Table 4. Implementing CE principles: A roadmap of opportunities for the oil and gas industry (made by the authors).

Industry Areas	Production Processes in the Oil and Gas Industry	Potential Technological Solutions	Contribution to CE Principles Implementation
1. APG utilization	Extraction	- Reinjection into reservoirs during gas-condensate field development to maintain reservoir pressure and enhance oil recovery; - Use as fuel for heat and power generation; - Refining at gas-processing plants to produce LPG, which serves as feedstock for manufacturing products with a variety of chemical compositions; - “Gas-to-liquids” (chemical conversion of APG into liquid fuels); - Production of synthetic crude oil via beta conversion of hydrocarbons (exposure of hydrocarbon molecules to accelerated electrons (beta particles) and microwave irradiation).	- Prevention of gas flaring, minimization of valuable resource losses, reduction in environmental pollution, decreased need for new fields development, application in EOR processes (aligns with reduce and reuse principles); - Deployment as fuel for autonomous power plants, and CHPP (recover); - Production of high-value products, power generation (recycle, recover).
2. CCUS	Drilling, extraction, transportation, refining	- Disposal in depleted or partially depleted oil and gas reservoirs, application for EOR; - Use in concrete production; - Utilization as petrochemical feedstock (production of methanol, DME, synthetic fuels, polymers, urea, and other chemical products); - Use for neutralization of alkaline effluents; - Use as a solvent (CO₂ in a supercritical state), refrigerant.	- Reduction in GHG emissions and sectoral carbon footprint, extension of the field operational life, and decreased need for new field development (reduce); - reuse in production processes (reuse); - Recovery of high-value products, power generation (recycle, recover).
3. Drilling sludge management	Drilling, extraction	- Reinjection into formations; - Utilization of mineral fraction of drilling sludge for manufacturing construction materials and products, road surfaces, gravel, aluminosilicate proppants for hydraulic fracturing, biostimulants for plant growth, nanocomposite materials; - Processing of the hydrocarbon-rich liquid fraction to produce diesel fuel and fuel oil, bitumen, or for direct power generation.	- Prevention of environmental pollution, minimization of waste generation, (reduce); - Reuse of components in production processes (liquid fraction) (reduce, reuse); - Recovery of high-value products, power generation (recycle, recover).

Table 4. Cont.

Industry Areas	Production Processes in the Oil and Gas Industry	Potential Technological Solutions	Contribution to CE Principles Implementation
4. Oil sludge management	Extraction, refining, emergency oil spills, cleaning of tanks and other equipment, wastewater treatment	- Use of water following sludge separation for industrial purposes, and return of the recovered oil fraction to the production cycle; - Utilization of oil sludge as feedstock for manufacturing construction materials and products, adsorbents for wastewater treatment, biofertilizers, rubber tires, metal-based catalysts, carbon and clay composites; - Biogas production (anaerobic digestion).	- Prevention of environmental pollution, minimization of production waste generation, (reduce); - Reuse of components (water, hydrocarbon fractions) in technological processes (reduce, reuse); - recovery of high-value products, power generation (recycle, recover).
5. Enhanced recovery of conventional and unconventional oil and gas reserves	Extraction	- Horizontal drilling, hydraulic fracturing, and their combination; reinjection of produced waters into formations; - Chemical EOR methods through injection of polymer solutions, alkalis, surfactants, ammonia, or micellar solutions into the reservoir; - Combined EOR methods (hydrodynamic + thermal, hydrodynamic + physicochemical, thermal + physicochemical combinations, etc.); - EOR via injection of CO₂, liquefied gases, dry methane, or APG into formations; - Reservoir heating methods (injection of hot water or steam, in situ combustion, and thermo-gas stimulation); - EGR through acid treatment (injecting hydrochloric acid solutions, including heated), hydraulic fracturing, mechanical stimulation (torpedoing), or sampling under vacuum, CO₂ injection (CO₂-EGR-CCUS).	- Reduction in the need for developing new fields, mitigation of environmental impact (reduce); - Closing the production loop, utilizing by-products (waste streams) in the technological process (produced water, CO₂, APG) (reduce, reuse); - Repurposing depleted oil and gas fields as CO₂ storage reservoirs (repurpose).

Table 4. Cont.

Industry Areas	Production Processes in the Oil and Gas Industry	Potential Technological Solutions	Contribution to CE Principles Implementation
6. Treatment and reuse of wastewater and produced water	Extraction, refining	- Wastewater treatment and its reuse in production processes; - Subsurface injection for EOR or formation pressure maintenance; - Use for various industrial applications (such as dust control, vehicle washing, make-up water for power plants, firefighting systems, etc.); - Treatment and reuse for controlled agricultural irrigation, livestock, and wildlife watering; - Processing recovered hydrocarbons to produce valuable products; - Utilization of recovered hydrocarbons for heat generation; - Extraction of valuable components (lithium, bromine, iodine, boron, potassium, etc.).	- Prevention of environmental pollution, minimization of waste generation, and freshwater consumption (reduce); - Reuse within technological processes; utilization for industrial and agricultural applications (reduce, reuse, repurpose); - Recovery of high-value products, power generation (recycle, recover).
7. Increasing crude oil refining depth	Refining	- Increasing yield of motor fuels and petrochemical feedstock through expansion of secondary oil refining capacities; - Extension of motor fuels output, production of hydrogen, methanol, sulfur, and electricity through processing of petroleum residue, implementing residue-free oil refining schemes; - Extension of motor fuels output by co-processing of petroleum residues with solid organic waste (including plastics, end-of-life tires, etc.); - Substituting heavy fuels in transportation (particularly maritime shipping), optimization of fuel consumption structure.	- Prevention of environmental pollution and minimization of waste generation in petroleum refining processes (reduce); - Recovery of high-value products, power generation (recycle, recover); - Generation of electricity for internal consumption (recover); - Shifting major consumers of petroleum products towards higher-quality fuels; transformation of refineries to process waste feedstock (rethink).

Table 4. Cont.

Industry Areas	Production Processes in the Oil and Gas Industry	Potential Technological Solutions	Contribution to CE Principles Implementation
8. Processing heavy crude oils and natural bitumen	Refining	- Conversion into “synthetic crude oil” for subsequent production of motor fuels, lubricating oils, and petrochemical products; - Extraction and utilization of specific components (oxygen-containing organic compounds, vanadium, nickel, and other rare non-ferrous metals); - Production of asphalt concrete, processing into paving bitumen for road-construction applications.	- Prevention of environmental pollution and minimization of waste generation (reduce); - Recovery of high-value products, power generation (recycle, recover).
9. Processing spent lubricating oils	Refining	- Processing to produce base oils; - Processing to produce fuel oil; - Incineration in cement kilns, industrial boilers, power plants, or cogeneration facilities to generate heat and electricity, or use as an additive to heavy marine fuel; - Heat and power generation from low-value by-products (gas); - Use of oil refining residues as an additive in paving bitumen.	- Prevention of environmental pollution, minimization of primary resource consumption and waste generation (reduce); - Regeneration with subsequent reuse (remanufacture); - Heat and power generation (recover); - Recovery of high-value products (recycle, recover).
10. Regeneration and recycling of spent catalysts	Refining	- Regeneration and subsequent rejuvenation for reuse; - Utilization of thermal energy generated during regeneration processes (coke and sulfur combustion); - Processing to recover valuable metals; - Use as feedstock for manufacturing construction materials; - Reuse as catalysts for the production of synthetic fuels or zeolite manufacturing; - Direct use (without pretreatment) as an adsorbent for wastewater treatment.	- Prevention of environmental pollution, minimization of primary resource consumption and waste generation (reduce); - Regeneration with subsequent reuse (refurbish, remanufacture); - Reuse within the oil and gas industry and across other sectors (reuse); - Processing to extract valuable components and recover energy (recycle, recover).

Table 4. Cont.

Industry Areas	Production Processes in the Oil and Gas Industry	Potential Technological Solutions	Contribution to CE Principles Implementation
11. Reducing evaporation losses of crude oil and petroleum products	Transportation and storage	- Reduction in internal oil transfers within the terminal, continuous sealing of petroleum transportation system components, and optimization of tank filling operations; - Installation of VRU systems; - Creation of a physical barrier between the stored product and the ambient atmosphere; - Reducing temperature fluctuations in the vapor space (ullage) of storage tanks; - Creation of an inert atmosphere in the vapor space of the storage tank; - Introducing micro-quantities of surfactants into petroleum product storage tanks.	- Prevention of environmental pollution and reduction in valuable feedstock/products losses (reduce).
12. Decommissioning of production facilities in accordance with CE principles	All production processes	- Modularization of structures at the design stage; - Recertification and reuse of equipment; - Repurposing of infrastructure; - Recycling of materials; - Land rehabilitation.	- Prevention of environmental pollution, minimization of waste generation, and reduction in resource losses (reduce); - Direct reuse or repurposing for alternative applications (reuse, repurpose); - Processing to recover valuable products/components (recycle); - Transition to designs enabling easy disassembly, and reframing site land as natural capital (rethink).

Direction 5 (enhanced recovery of conventional and unconventional oil and gas reserves) contributes to the reduce, reuse, and repurpose principles. Direction 7 (increasing oil refining depth), Direction 8 (processing heavy oils and natural bitumen), and Direction 9 (processing spent lubricating oils) contribute to the reduce, recycle, and recover principles. Direction 7 additionally advances the rethink principle, while Direction 9 contributes to remanufacture. Direction 11 (reducing evaporation losses of crude oil and petroleum products) contributes to the reduce principle, while Direction 12 (decommissioning production facilities according to CE principles) advances five principles: rethink, reduce, reuse, repurpose, and recycle (Figure 6).

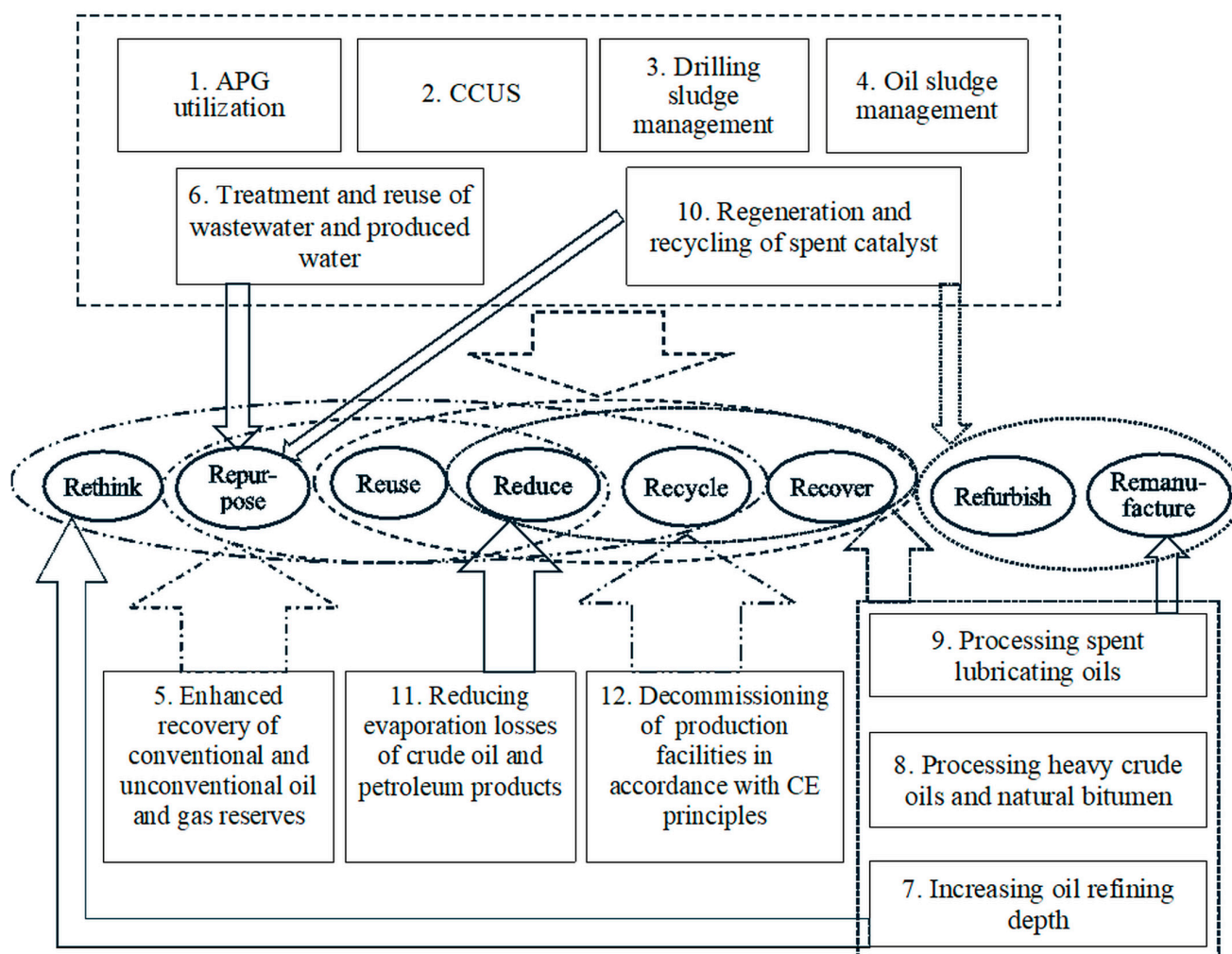


Figure 6. Vectors of CE principles implementation in the oil and gas industry (made by the authors).

It should be noted that land rehabilitation during decommissioning constitutes the restoration of natural capital, which strictly speaking extends beyond the 10R framework and aligns with the regenerate principle—corresponding to the biological cycle of the CE. However, rehabilitation can also be interpreted through the lens of the rethink, reduce, and reuse principles.

Significant technological interlinkages exist among several of the discussed directions, fostering synergistic impacts and enabling loop closure. Specifically:

- APG, CO₂, produced water, and wastewater can be utilized for EOR;
- CO₂ can be sequestered or stored (with potential for subsequent utilization) in depleted oil and gas reservoirs; sc-CO₂ can be applied in the regeneration and recycling of spent catalysts and the treatment of drilling waste;

- Oil sludge can be processed to yield adsorbents for wastewater treatment and technical-grade water;
- Hydrocarbons recovered from drilling waste, oil sludge, and spent lubricating oils are returned to the refining stage, thereby increasing overall refining depth;
- Regenerated and reactivated catalysts can be employed to enhance refining depth and process heavy oils, while catalysts unsuitable for regeneration can be repurposed as adsorbents for wastewater treatment.

4.2. Contribution of Key CE Implementation Pathways in the Oil and Gas Industry to Achieving SDGs

Although the circularity of material flows and/or supply chains is widely recognized as an approach to advancing sustainable development [56], at the present stage, this conclusion remains ambiguous for the energy sector as a whole, and particularly for the oil and gas industry, since the CE principles are being implemented within a traditional linear model that relies dominantly on fossil fuels.

Industry-specific practices for CE transition generate both positive outcomes and additional economic and environmental costs. The direction and magnitude of their impact on achieving global SDGs will depend on the balance between these benefits and costs, which is primarily determined by the availability and maturity of technologies employed to mitigate adverse effects.

This section analyzes the nature of the influence of the considered industry-specific CE implementation pathways on the SDGs.

APG utilization and CCUS generate a direct positive impact on multiple SDGs. In particular, they advance SDG 7 “Affordable and clean energy” by converting APG into usable power and thermal energy while CCUS technologies installation reduces the carbon footprint from fossil fuels. They support SDG 8 “Decent Work and Economic Growth”. Both considered directions enhance the economic efficiency of the oil and gas industry and contribute to the creation of new production facilities and employment. They stimulate SDG 9 “Industry, Innovation and Infrastructure”. The development of innovative technologies for APG processing and CCUS drives the growth in the petrochemical sector (e.g., converting APG into high-value feedstock), and supports the modernization of production processes and infrastructure. These pathways align with SDG 12 “Responsible Production and Consumption” by preventing losses of valuable hydrocarbon resources and enhancing the sustainability of hydrocarbon resource use, and with SDG 13 “Climate Action” through the mitigation of GHG emissions (CO_2 , CH_4).

Moreover, these directions contribute to SDG 14 “Life below water” by slowing ocean acidification and marine pollution; SDG 15 “Life on Land” by reducing atmospheric air and soil contamination, mitigating land degradation, lessening climate-related ecosystem stressors, and preserving biodiversity; SDG 3 “Good Health and Well-Being” by improving environmental conditions, enhancing air quality, and mitigating public health risks.

Finally, CCUS positively influences SDG 17 “Partnership for the Goals”, as it represents a high-technology, knowledge-intensive field, whose advancement is impossible in isolation. It also fosters scientific and technological transfer and comprehensive international cooperation for sustainable development.

The widespread deployment of APG utilization and CCUS faces several negative effects and implementation barriers. They include the need for substantial capital investments, high energy consumption, risks of leakages from subsurface storage tanks and pipelines, which could result in adverse environmental consequences, and the potential for induced seismicity associated with high-volume gas injections. Nevertheless, the net impact of these pathways on achieving the UN Global Goals within the oil and gas industry remains profoundly positive. The beneficial effects are systemic in nature and fundamen-

tally more significant: the global mitigation of the greenhouse effect, long-term resource conservation, and the establishment of the robust technological foundation for the energy transition. The identified negative effects primarily represent technological challenges rather than inherent limitations; these barriers are expected to diminish as innovative solutions develop and become more accessible and cost-competitive.

Drilling and oil sludge management in accordance with CE principles positively influences the achievement of SDG 8 by creating new employment opportunities in sludge handling and treatment operations and contributing to economic growth; SDG 9 through the development of innovative, eco-oriented technologies for drilling and oil sludge processing and valorizing, alongside associated infrastructure modernization; SDG 12 by decreasing the primary resource consumption and minimizing waste generation; SDG 14 by preventing marine pollution caused by improper disposal of drilling sludge and avoiding oil sludge infiltration into aquatic ecosystems; and SDG 15 by mitigating soil contamination, land degradation and reducing threats to biodiversity. Additionally, beneficial impact is observed for SDG 3 (reduction in public health risks, prevention of environmental pollution) and SDG 6 “Clean Water and Sanitation” (prevention of groundwater and surface water pollution).

However, there are certain environmental risks that could potentially undermine progress towards achieving SDGs 14, 15, 6, and 3. Such risks may arise, for example, from secondary pollution generated during thermal sludge treatment, residual heavy metal content in soil blends derived from process sludge, or other unintended by-products. These challenges necessitate rigorous monitoring of secondary emissions and deployment of the best available techniques (BAT) for their mitigation. Nevertheless, active sludge processing, while introducing localized, manageable local risks, delivers significant advantages for achieving the aforementioned SDGs, whereas conventional landfilling poses critical, long-term environmental threats. Therefore, its overall impact remains decisively positive if BAT is systematically applied.

The impact of these CE implementation directions on SDG 13 is ambiguous. While GHG emissions are reduced by preventing methane release associated with the anaerobic decomposition of organic sludge components during storage, many processing technologies are energy-intensive and significantly contribute to GHG emissions when powered by fossil fuels. Furthermore, the overall carbon footprint may increase due to transportation logistics if sludge is processed off-site. The climate impact, nonetheless, can be positive when processing BAT is selected.

It is also critical to account for methane’s global warming potential, which is approximately 80 times higher than that of CO₂ over a 20-year horizon. According to [195], landfilling sludge generates 20–30 kg CO₂-eq per ton of waste due to methane emissions, while incineration adds a further 50 kg CO₂-eq per ton. Consequently, when factoring in avoided methane emissions combined with on-site processing and a shift from landfilling to resource recovery and the production of valuable secondary products, the overall climate impact is likely positive.

Economic barriers are primarily linked to the substantial capital expenditure required for modern processing facilities, and the high production cost of secondary raw materials derived from sludge, which increases the final cost of end products (e.g., construction materials). Market competitiveness of such products can be enhanced through government subsidies, and coupled with ongoing technological advancements, this will gradually enable broader adoption and scale-up of these CE directions over time.

Enhanced recovery of conventional and unconventional oil and gas reserves has a beneficial effect on SDG 8 (by generating employment and stimulating economic development), on SDG 9 (through implementing innovative technologies and associated infrastructure

development), and on SDG 12 (by improving field development efficiency and promoting more responsible utilization of hydrocarbon resources).

The influence on SDG 7 is ambiguous: while enhancing the recovery rate of fossil fuels increases their availability and strengthens energy security, it may slow the global energy transition. The potential effect on SDG 14 and SDG 15 is also mixed due to potential risks of aquatic ecosystem pollution, soil contamination, and land degradation, necessitating the deployment of environmental protection technologies to mitigate environmental impacts.

The impact on SDG 17 is positive as it facilitates cross-border transfer of scientific knowledge, global value chain integration, technological progress, and the groundwork for energy partnerships. However, the efficiency of this contribution may temporarily diminish under conditions of geopolitical tension.

The influence on SDG 13 is negative, as increased oil and gas extraction and combustion of hydrocarbons elevate GHG emissions and exacerbate climate risks. However, future integration of enhanced recovery methods with CCUS technologies could neutralize this climate impact. Negative effects also extend to SDG 6 due to increased water consumption and elevated contamination risks compared to conventional oil and gas extraction, and to SDG 3 due to potential public health impacts in extraction zones.

To ensure a net-positive contribution to SDGs, enhanced recovery practices must be combined with improvements in the energy efficiency of processes, deployment of BAT, CCUS integration, energy mix diversification, improved environmental performance, and reducing environmental pollution risks. It is also important to note that EOR/EGR technologies entail significantly higher capital and operational costs compared to conventional extraction methods.

Treatment and reuse of wastewater and produced water exerts a positive influence on SDG 6, by reducing freshwater consumption and mitigating pollution of natural water bodies, and SDG 9, through the deployment of innovative water treatment technologies and implementation of closed-loop water supply systems. It indirectly affects SDG 2 “Zero Hunger” by increasing freshwater availability for agriculture, supporting food security, and reducing competition for freshwater resources between the oil and gas industry and farming. Positive effects also extend to SDG 12 via improved water use efficiency and reduced waste generation, and to SDGs 14 and 15 through lower pollutant loads in ecosystems, minimized wastewater discharge, climate change mitigation, and biodiversity conservation.

The impact on SDG 3 is generally positive due to improved community health near production facilities; however, occupational health risks for personnel at treatment facilities associated with advanced purification processes must be carefully assessed and mitigated. The influence on SDG 13 is ambiguous: advanced wastewater and produced water treatment is highly energy-intensive, making the net climate impact dependent on the energy source (the positive impact on SDG 13 in perspective is only possible with the use of renewable energy sources or APG). It should also be noted that deployment of these treatment technologies entails substantial capital expenditures.

Increasing crude oil refining depth positively contributes to SDG 8 (by creating new jobs and stimulating GDP growth), SDG 9 (via refinery modernization, development of new processing technologies and production facilities and supporting infrastructure advancement), and SDG 12 (by minimizing waste generation and improving the efficiency of crude oil utilization). It also advances SDG 17 by fostering international cooperation, exchange of scientific knowledge, technology transfer, and foreign investment; though, this effect may diminish amid geopolitical instability.

The impact on SDG 6 is ambiguous: deep conversion is water-intensive and may compete with municipal and agricultural demands in regions experiencing freshwater scarcity. However, adopting BAT, implementing closed water supply cycles, and enforcing

strict effluent quality controls can maintain a neutral net impact. The influence on SDG 7 is also mixed: while deeper refining yields cleaner fuels that better satisfy demand for high-quality petroleum products and reduce tailpipe toxic emissions, the increased energy consumption for processing elevates emissions of air pollutants. The final outcome depends on the technologies applied and the product produced.

The effects of increasing oil refining depth on SDGs 14 and 15 are similarly ambiguous. Uncontrolled capacity expansion without corresponding upgrades to environmental protection systems increases contamination of aquatic ecosystems by wastewater, soil pollution, landscape disruption, and biodiversity loss. However, modern refineries equipped with advanced environmental controls exhibit no adverse effects on these SDGs. The impact on SDG 3 is technology-dependent, as environmental changes affecting public health vary with the technologies deployed.

The high energy intensity of deep refining processes leads to increased GHG emissions that negatively influence SDG 13. Future climate neutrality may be achievable through integration with CCUS and petrochemical valorization pathways.

Consequently, maximizing sustainable outcomes requires coupling deep refining with: (i) integration of CCUS technologies; (ii) energy efficiency optimization; (iii) adoption of BAT for environmental protection; (iv) environmental risk mitigation; and (v) energy diversification. While these measures could significantly mitigate negative impacts, they necessitate substantial capital expenditure.

Processing heavy crude oils and natural bitumen has a role to play in achieving SDG 8 (by generating employment and stimulating GDP growth), and SDG 9 (through the development of new environmentally friendly processing technologies and infrastructure advancement). The influence on SDG 7 is mixed: while it enhances the availability of energy resources and strengthens energy security, processing operations are highly energy-intensive and generate environmental pollution from process by-products. A similarly ambiguous effect is observed for SDG 12: although feedstock utilization efficiency improves, high energy and water intensity, along with the generation of complex, hard-to-treat waste streams (which are minimized through deep conversion configurations).

Negative impacts are noted for SDG 13 due to increased GHG emissions and associated climate effects; SDG 14 owing to increased spill risks and adverse effects on marine ecosystems; SDG 15 through atmospheric and soil contamination, land degradation, and threats to biodiversity; and SDG 6 due to intensified pressure on water resources from refining operations. As a consequence of these adverse effects, SDG 3 is also negatively affected, reflecting increased risks of environmental degradation and associated public health concerns.

To ensure sustainable outcomes, the development of heavy crude oil and natural bitumen processing must be integrated with (i) improvements in the energy efficiency of the processes; (ii) CCUS deployment; (iii) implementation of a closed water supply cycle; (iv) an increase in environmental indicators; (v) environmental risk mitigation; and (vi) diversification of energy carriers. Given the physicochemical complexity of this feedstock, addressing these sustainability challenges is technologically more complex and requires substantial capital investment.

Processing spent lubricating oils positively contributes to SDG 9 through the development of advanced recycling technologies and infrastructure; SDG 12 by reducing demand for virgin petroleum resources and minimizing waste generation; and SDG 13 by mitigating GHG emissions and climate impacts, associated with primary oil refining, driven by decreased crude oil consumption.

The impact on SDGs 14 and 15 is ambiguous: risks of environmental contamination arise from non-compliance with processing and storage protocols, but these can be effec-

tively mitigated through strict regulatory adherence. Similarly, the influence on SDG 3 is also mixed: the effect on environmental quality and public health is determined by compliance with environmental standards for processing, proper waste oil handling practices, and ultimately the net balance between avoided emissions and pollution released into the environment. Achieving sustainable outcomes requires coupling processing spent lubricating oils with rigorous compliance with environmental standards and regulations, and the deployment of BAT. Currently, challenges persist in the collection and transportation of spent lubricating oils, resulting in a significant volume being incinerated rather than recycled [195,196].

Regeneration and recycling of spent catalysts exert a positive influence on SDG 8 by creating employment opportunities in the high-tech catalyst recycling sector; SDG 9 through the development of innovative regeneration and recycling technologies for spent catalysts; SDG 12 by reducing resource consumption and waste generation; SDG 13 by lowering GHG emissions through the avoidance of energy-intensive primary metal extraction; and SDG 15 by mitigating ecosystem impacts caused by extraction of valuable metals, thereby preserving landscapes and biodiversity.

The impact on SDG 6 remains controversial owing to substantial wastewater generation, which, in the absence of a closed water circulation system, poses a potential risk of groundwater contamination by residual hydrocarbons and heavy metals. Thus, the ultimate impact depends on the technologies deployed.

Principal constraints to the widespread recycling of spent catalysts include technical complexities and high costs associated with logistics, safe collection, transportation, and processing, as well as volatility in metal prices [197].

Reducing evaporation losses of crude oil and petroleum products has a beneficial effect on SDG 7 by improving energy availability through more efficient resource utilization, reducing extraction demand, and lowering environmental pollution associated with energy use. It also positively contributes to achievement of SDG 9 through development and deployment of advanced vapor recovery technologies; SDG 12 by minimizing waste volumes, preventing losses of valuable hydrocarbon resources and enhancing overall resource efficiency; SDG 13 via reduction in GHG emissions, driven by lower atmospheric release of VOCs that contribute to tropospheric ozone formation; and SDG 15 by mitigating soil and water bodies contamination, and supporting biodiversity conservation. Additionally, favorable outcomes extend to SDG 6 through the prevention of water bodies contamination by petroleum products, e.g., via rainwater runoff, and to SDG 3 by improving environmental quality, particularly atmospheric air, and reducing public health risks.

Despite the need for substantial initial investments, particularly for large-scale enterprises, challenges in retrofitting legacy fixed-roof storage tanks, and certification requirements for novel vapor capture approaches, the global vapor recovery systems market is projected to grow at a compound annual growth rate of 5.4% through 2034 [198].

Decommissioning of production facilities in accordance with CE principles positively advances SDG 7 by reducing the sector's carbon footprint through secondary resource utilization, increasing energy efficiency and repurposing production facilities for renewable energy infrastructure; SDG 8 by the creating new employment opportunities requiring high-qualified specialists; SDG 9 through the development of innovative decommissioning technologies and infrastructure; SDG 12 by minimizing waste generation, reducing primary resource consumption and maximizing the reuse of materials and components. Positive impacts also extend to SDG 13 by mitigating GHG emissions consequent to diminished demand for primary raw materials extraction and new materials manufacturing, SDG 14 through the reduction in marine pollution and the facilitation of biodiversity

restoration, and SDG 15 via ecological rehabilitation, recultivation, and revitalization of degraded lands.

The transition toward circular decommissioning of production facilities necessitates the implementation of government incentive programs due to the substantial upfront capital requirements. Moreover, legacy facilities were predominantly designed without modularity considerations, rendering the non-destructive extraction of most materials and components technologically infeasible under current engineering constraints.

The results of the analysis examining the impact of the considered CE implementation pathways on the SDGs are systematized in Table 5.

Thus, for the majority of the assessed directions, the influence on the SDGs is predominantly positive: 4 out of 12 pathways demonstrate mostly positive impacts, with an additional five exhibiting either positive or mixed (context-dependent) effects, despite the existing technological and economic challenges. Conversely, 3 out of 12 key directions (enhancing recovery of conventional and unconventional oil and gas reserves; increasing crude oil refining depth; and, in particular, processing heavy crude oils and natural bitumen) present significant challenges to achieving certain SDGs given current technological capabilities.

However, these adverse impacts can be mitigated through enhanced synergy with other CE implementation pathways (including CCUS), deployment of BAT, improvements in production energy efficiency, and the implementation of coordinated government support and regulatory measures.

4.3. Shifting the Management Paradigm Under the Circular Transformation in the Oil and Gas Industry

The conducted analysis and systematization serve as the foundation for defining core management principles for oil and gas companies and projects, aligned with sustainable development priorities and the transition to a CE, thereby enabling the transformation of costs into new value streams:

1. Rational and comprehensive subsurface utilization and preservation of resource potential (key directions of CE principles implementation: 1, 5, 7, 8, and 11);
2. Integrated recovery of valuable components from production waste to generate secondary marketable products) (key directions of CE principles implementation: 6 and 10);
3. Closing technological loops (water, drilling fluids, lubricating oils, etc.) and minimizing the consumption of primary resources and chemical reagents (key directions of CE principles implementation: 3, 4, 6, and 9);
4. Carbon management and closing the carbon cycle (key direction of CE principles implementation 2);
5. Cross-sectoral collaboration and valorization of production waste into useful products (key directions of CE principles implementation: 3, 4, and 10);
6. Land regeneration and recultivation with proactive decommissioning planning (key directions of CE principles implementation: 6 and 12);
7. Circular asset management with modular design (key directions of CE principles implementation: 12).

Table 5. Impact of key directions of CE principles implementation in the oil and gas industry on achieving the SDGs * (made by the authors).

Key Directions of CE Principles Implementation	Implemented CE Principles	Sustainable Development Goals										
		SGD 2 Zero Hunger	SDG 3 Good Health and Well-Being	SDG 6 Clean Water and Sanitation	SDG 7 Affordable and Clean Energy	SDG 8 Decent Work and Economic Growth	SDG 9 Industry, Innovation and Infrastructure	SDG 12 Responsible Consumption and Production	SDG 13 Climate Action	SDG 14 Life Below Water	SDG 15 Life on Land	SDG 17 Partnerships for the Goals
1. APG utilization	Reduce, Reuse, Recycle, Recover											
2. CCUS	Reduce, Reuse, Recycle, Recover											
3. Drilling sludge management	Reduce, Reuse, Recycle, Recover											
4. Oil sludge management	Reduce, Reuse, Recycle, Recover											
5. Enhanced recovery of conventional and unconventional oil and gas reserves	Reduce, Reuse, Repurpose											
6. Treatment and reuse of wastewater and produced water	Reduce, Reuse, Repurpose, Recycle, Recover											
7. Increasing crude oil refining depth	Rethink. Reduce, Recycle, Recover											
8. Processing heavy crude oils and natural bitumen	Reduce, Recycle, Recover											
9. Processing spent lubricating oils	Reduce, Remanufacture, Recycle, Recover											
10. Regeneration and recycling of spent catalysts	Reduce, Reuse, Refurbish, Remanufacture, Recycle, Recover											
11. Reducing evaporation losses of crude oil and petroleum products	Reduce											
12. Decommissioning of production facilities in accordance with CE principles	Rethink, Reduce, Reuse, Repurpose, Recycle											

* —positive impact; —negative impact; —ambiguous impact; —no impact.

These new principles, which must encompass both operational processes and corporate strategy, fundamentally reshape management requirements for oil and gas companies. First and foremost, the interdisciplinary nature of circular transition tasks necessitates the formation of dedicated project teams comprising specialists from diverse fields, alongside clear resource allocation and decision-making authority delegated to team leaders. The incentive systems require enhancement through the integration of performance indicators aligned with the proposed fundamental management principles. Investment justification must incorporate cost analysis and material flow tracking across the entire asset lifecycle, primarily leveraging advanced digital monitoring systems, and prioritize capital allocation in accordance with these core principles. A critical requirement is the development of new mechanisms for intra- and inter-industry partnerships, as well as engagement with research institutions and the public.

Although the impact of the oil and gas industry on achieving SDGs has received scholarly attention [13–15,19], and certain studies focusing on specific initiatives attributable to CE principles in the sector have noted their contribution to SDG advancement [120], this research presents the first systematic identification of priority sectoral directions for implementing CE principles and a comprehensive qualitative assessment of their impact on SDGs achievement. The reliance on qualitative decomposition can be considered as a research limitation, while, for example, the methodological framework [199] proposed a quantitative decision support system. The elaboration of practical instruments for quantitative assessment is a promising direction for future research.

Although directions for implementing CE principles are currently being introduced within a predominantly linear economic model, they enable the active participation of the oil and gas industry in the transition to a CE, contingent upon balancing energy security and environmental sustainability. The systematic mapping presented herein reveals qualitative patterns of sectoral transformation, while the distribution of key directions across the production value chain demonstrates the potential for end-to-end resource efficiency, closed-loop material flows, waste minimization, and contributions to climate change mitigation.

Advancing each priority direction and enhancing its technological maturity is essential for preserving the role of the oil and gas industry in the global energy balance while simultaneously complying with sustainability criteria.

5. Conclusions

In the context of the global energy transition and escalating environmental challenges, transitioning towards a CE model and aligning with the SDGs enable the oil and gas industry to achieve a fundamentally new development level, ensuring its competitiveness, rational resource utilization, and mitigation of environmental impact. The present study focused on the investigation of circular transformation in the oil and gas industry and its contribution to achieving SDGs. The following conclusions, addressing research questions, can be formulated:

- (1) A total of 12 industry-specific key directions for implementing CE principles and technological capabilities for each direction were identified and analyzed, including well-developed (e.g., VRU, wastewater treatment) and innovative approaches (e.g., co-processing of organic waste with petroleum residues, valuable metals extraction from produced water).
- (2) A systematic decomposition of the interrelations between each industry-specific key direction and CE principles, with examination of emerging synergistic effects, demonstrated multidimensional relationships, and revealed that CE implementation in the oil and gas industry requires diversified approaches.

- (3) A qualitative assessment of the impact of identified directions on achieving SDGs was conducted. The results demonstrated synergy, as 12 directions contribute to achieving various SDGs, and also revealed existing challenges and barriers.
- (4) A study demonstrates that transformation of the management paradigm in the context of transition to a CE and sustainable development priorities is required and formulates the basic management principles for oil and gas companies, which necessitate new interdisciplinary competences.

The results of this study provide a foundation for transitioning from fragmented practices to a purposeful transformation of the oil and gas industry, enabling the complex exchange of resources, waste minimization, contributions to the achievement of SDGs, and alignment of interests among key stakeholders in this process.

The research contributes to the theoretical understanding of CE implementations in the industries, traditionally considered as linear. The findings not only provide a methodological basis for strategic management and planning at the oil and gas enterprises that integrate CE principles and SDGs but can also be applied to support the modernization of industry standards and justify government support measures. The research holds practical value for enhancing sustainability reporting practices in oil and gas companies. Establishing a link between technological initiatives, CE principles, and global SDGs indicators ensures transparency regarding corporate environmental contributions and enhances the relevance of disclosed information for potential investors.

The proposed methodology could be scaled across the entire FEC. Future research will focus on developing a practical self-assessment toolkit for the evaluation of the industry enterprises' compliance with CE principles, alongside a structured roadmap for implementing corresponding development strategies.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
APG	Associated Petroleum Gas
BAT	Best Available Techniques
CCUS	Carbon Capture, Utilization, and Storage
CE	Circular Economy
CHPP	Combined Heat and Power Plant
DME	Dimethyl Ether
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
FCC	Fluid Catalytic Cracking
FSRU	Floating Storage Regasification Unit
FEC	Fuel and Energy Complex
GBDF	Gas-Based Drilling Fluids
GHG	Greenhouse Gas
HTF	Hard-to-Recover
IEA	International Energy Agency
IPIECA	International Petroleum Industry Environmental Conservation Association
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
OBDF	Oil-Based Drilling Fluids
PAHs	Polycyclic Aromatic Hydrocarbons
RES	Renewable Energy Sources
SAF	Synthetic Aviation Fuel
SBDF	Synthetic-Based Drilling Fluids
SFE	Supercritical Fluid Extraction
VOCs	Volatile Organic Compounds
VRU	Vapor Recovery Units
WBDF	Water-Based Drilling Fluids

References

1. Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation. 2013. Available online: <https://www.ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition> (accessed on 1 January 2026).
2. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. European Commission. 2008. Available online: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN> (accessed on 1 January 2026).
3. Bag, S.; Gupta, S.; Kumar, S. Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. *Int. J. Prod. Econ.* **2021**, *231*, 107844. [CrossRef]
4. Sihvonen, S.; Ritola, T. Conceptualizing ReX for Aggregating End-of-life Strategies in Product Development. *Procedia CIRP* **2015**, *29*, 639–644. [CrossRef]
5. Reike, D.; Vermeulen, W.J.V.; Witjes, S. The circular economy: New or refurbished as CE 3.0?—Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resour. Conserv. Recycl.* **2018**, *135*, 246–264. [CrossRef]
6. Danish, M.S.S.; Senjyu, T. Shaping the future of sustainable energy through AI-enabled circular economy policies. *Circ. Econ.* **2023**, *2*, 100040. [CrossRef]
7. Mhatre, P.; Panchal, R.; Singh, A.; Bibyan, S. A systematic literature review on the circular economy initiatives in the European Union. *Sustain. Prod. Consum.* **2021**, *26*, 187–202. [CrossRef]
8. Uvarova, I.; Atstaja, D.; Volkova, T.; Grasis, J.; Ozolina-Ozola, I. The typology of 60R circular economy principles and strategic orientation of their application in business. *J. Clean. Prod.* **2023**, *409*, 137189. [CrossRef]
9. Magaril, E. The Solution to Strategic Problems in the Oil Refining Industry as a Factor for the Sustainable Development of Automobile Transport. *WIT Trans. Ecol. Environ.* **2014**, *190*, 821–832. [CrossRef]

10. Shahbaz, M.; Rashid, N.; Saleem, J.; Mackey, H.; McKay, G.; Al-Ansari, T. A review of waste management approaches to maximize sustainable value of waste from the oil and gas industry and potential for the State of Qatar. *Fuel* **2023**, *332*, 126220. [CrossRef]
11. *Management of Exploration, Development and Production Wastes*; EPA 530-R-19-007; United States Environmental Protection Agency: Washington, DC, USA, 2019. Available online: https://www.epa.gov/sites/default/files/2019-04/documents/management_of_exploration_development_and_production_wastes_4-23-19.pdf (accessed on 15 June 2026).
12. Oil Spill Waste Minimization and Management. IPIECA. 2025. Available online: <https://www.ipieca.org/resources/oil-spill-waste> (accessed on 15 June 2026).
13. Borges, F.M.M.G.; Rampasso, I.S.; Quelhas, O.L.G.; Leal Filho, W.; Anholon, R. Addressing the UN SDGs in Sustainability Reports: An Analysis of Latin American Oil and Gas Companies. *Environ. Chall.* **2022**, *7*, 100515. [CrossRef]
14. Titova, N.; Cherepovitsyna, A.; Guseva, T. Meeting the UN's Sustainable Development Goals in the Decarbonization Agenda: A Case of Russian Oil and Gas Companies. *Resources* **2023**, *12*, 121. [CrossRef]
15. Okeke, A. Towards sustainability in the global oil and gas industry: Identifying where the emphasis lies. *Environ. Sustain. Indic.* **2021**, *12*, 100145. [CrossRef]
16. Dibia, F.; Dibia, C.; Dhakal, H.N.; Okpako, O.; Radulovic, J.; Isike, A. A Review on Achieving Sustainability in the Petroleum Industry Through the Integration of Lean and Green. *Appl. Sci.* **2025**, *15*, 2333. [CrossRef]
17. Cheng, X.; Chen, K.; Su, Y. Green innovation in oil and gas exploration and production for meeting the sustainability goals. *Resour. Policy* **2023**, *87*, 104315. [CrossRef]
18. Ma, W.; Dai, S.; Li, X.; Lu, H. Sustainable separation of oil from oily wastes using ionic liquids regulated by CO₂. *J. Clean. Prod.* **2022**, *369*, 133096. [CrossRef]
19. Bathrinath, S.; Abuthakir, N.; Koppiahraj, K.; Saravanasankar, S.; Rajpradeesh, T.; Manikandan, R. An initiative towards sustainability in the petroleum industry: A review. *Mater. Today Proc.* **2021**, *46*, 7798–7802. [CrossRef]
20. Sharma, M.; Joshi, S.; Prasad, M.; Bartwal, S. Overcoming barriers to circular economy implementation in the oil & gas industry: Environmental and social implications. *J. Clean. Prod.* **2023**, *391*, 136133. [CrossRef]
21. Mapping the Oil and Gas Industry to the Sustainable Development Goals: An Atlas. July 2017. IPIECA. Available online: <https://www.ipieca.org/resources/awareness-briefing/mapping-the-oil-and-gas-industry-to-the-sustainable-development-goals-an-atlas/> (accessed on 20 December 2025).
22. Research Report: Circular Economy Indicators, Potential for Use in the Oil and Gas Industry 2nd Edition. IPIECA. Available online: <https://www.ipieca.org/resources/research-report-circular-economy-indicators> (accessed on 15 December 2025).
23. Hasan, J.; Thomas, A.; Tomos, O. Sustainable Supply Chain Practices in the Oil and Gas Industry: A Case Study. *Sustainability* **2024**, *16*, 1720. [CrossRef]
24. Legorburu, I.; Johnson, K.R.; Kerr, S.A. Multi-use maritime platforms—North Sea oil and offshore wind: Opportunity and risk. *Ocean Coast. Manag.* **2018**, *160*, 75–85. [CrossRef]
25. Camarillo, M.K.; Stringfellow, W.T. Biological treatment of oil and gas produced water: A review and meta-analysis. *Clean Technol. Environ. Policy* **2018**, *20*, 1127–1146. [CrossRef]
26. Khlaifat, A.; Fakher, S.; Ezzat, F.H.; Alalaween, M.; Galitos, J. Integrating Circular Economy Principles in Petroleum Produced Water Management: Toward Sustainable Resource Recovery and Waste Minimization. *Processes* **2025**, *13*, 3604. [CrossRef]
27. L'Abate, V.; Esposito, B.; Sica, D.; Supino, S. Fueling the circular transition: An empirical exploration of sustainable development goal performance in the oil and gas industry. *Meas. Bus. Excell.* **2025**, *29*, 285–305. [CrossRef]
28. The Global Gas Flaring Tracker Report, 2024. World Bank's Global Flaring and Methane Reduction (GFMR). Available online: <https://thedocs.worldbank.org/en/doc/d01b4aebd8a10513c0e341de5e1f652e-0400072024/original/Global-Gas-Flaring-Tracker-Report-June-20-2024.pdf> (accessed on 10 November 2025).
29. Flared Gas Utilization Strategy. Opportunities for Small-Scale Uses of Gas. The International Bank for Reconstruction and Development. The World Bank. 2004. Available online: <http://documents.worldbank.org/curated/en/193801468779650307> (accessed on 10 November 2025).
30. Protocol of the Board Meeting of the Association of Oil Refiners and Petrochemists No. 156. Available online: https://oilref.ru/protocol/2021/156_2021.pdf (accessed on 1 September 2025). (In Russian)
31. Vershinin, S.A.; Blyabiyas, A.N.; Golovanov, D.A.; Penigin, A.V.; Glavnov, N.G. Technological Features of Associated Petroleum Gas Miscible Injection MGI in Order to Increase Oil Recovery at a Remote Group of Fields in Western Siberia. In Proceedings of the SPE Russian Petroleum Technology Conference, Online, 12–15 October 2021. [CrossRef]
32. Morenov, V.; Leusheva, E.; Buslaev, G.; Gudmestad, O.T. System of Comprehensive Energy-Efficient Utilization of Associated Petroleum Gas with Reduced Carbon Footprint in the Field Conditions. *Energies* **2020**, *13*, 4921. [CrossRef]
33. Afanasiev, V.Y.; Bolshakova, O.I.; Romantsov, A.A. Russian fuel and energy complex modernization in the circular economy direction. *Vestn. Univ.* **2023**, *12*, 62–71. (In Russian) [CrossRef]
34. Dvoynikov, M.; Buslaev, G.; Kunshin, A.; Sidorov, D.; Kraslawski, A.; Budovskaya, M. New Concepts of Hydrogen Production and Storage in Arctic Region. *Resources* **2021**, *10*, 3. [CrossRef]

35. Riadinskaia, A.; Cherepovitsyna, A. Associated Petroleum Gas Utilization: New Opportunities for the Oil and Gas Complex in a Circular Economy. *E3S Web Conf.* **2023**, *378*, 06006. [CrossRef]
36. Ebrahimi, H.; Zamaniyan, A.; Forsat, K. Improving Gas to Liquid Production by Associated Gases. *J. Petrol. Res. Stud.* **2017**, *7*, 211–225. [CrossRef]
37. Zolfaghari, M.; Pirouzfard, V.; Sakhaeinia, H. Technical characterization and economic evaluation of recovery of flare gas in various gas-processing plants. *Energy* **2017**, *124*, 481–491. [CrossRef]
38. Emissions from Oil and Gas Operations in Net Zero Transitions. A World Energy Outlook Special Report on the Oil and Gas Industry and COP28. IEA. 2023. Available online: <https://www.iea.org/reports/emissions-from-oil-and-gas-operations-in-net-zero-transitions> (accessed on 21 December 2025).
39. Kapitonov, S.; Osipov, A.; Gayda, I.; Lyashik, Y.; Grushevenko, E. Carbon Capture, Utilization, and Storage (CCUS) Technologies Technical Report. *Skoltech* **2022**, 41–43. (In Russian) [CrossRef]
40. Ward, C.; Heidug, W. *Enhanced Oil Recovery and CO₂ Storage Potential Outside North America: An Economic Assessment*; ks-2018-dp27; KAPSARC: Riyadh, Saudi Arabia, 2018; pp. 10–11. [CrossRef]
41. Emelyanov, K.; Zotov, N. Savings on decarbonization. *Energy Policy* **2021**, *10*, 26–37. (In Russian) [CrossRef]
42. Volkov, V.A.; Prokhorov, P.E.; Turapin, A.N.; Afanasev, S.V. Gas-cyclic injection of a carbon dioxide into oil production well for stimulation of production of high viscosity oil. *Neft. Gaz. Novatsii* **2017**, *4*, 62–66.
43. Mohammed-Singh, L.J.; Singhai, A.K.; Sim, S.S.-K. Screening Criteria for CO₂ Huff'n'Puff Operations. In Proceedings of the SPE/DOE Symposium on Improved Oil Recovery, Tulsa, OK, USA, 22–26 April 2006. [CrossRef]
44. Liu, Y.; Rui, Z. A Storage-Driven CO₂ EOR for a Net-Zero Emission Target. *Engineering* **2022**, *18*, 79–87. [CrossRef]
45. Pham, V.; Halland, E. Perspective of CO₂ for storage and enhanced oil recovery (EOR) in the North Sea. *Energy Procedia* **2017**, *114*, 7042–7046. [CrossRef]
46. Kramer, D. Negative carbon dioxide emissions. *Phys. Today* **2020**, *73*, 44–51. [CrossRef]
47. Bhowan, A.S.; Bromhal, G.; Barki, G. CO₂ capture and sequestration. In *Fossil Energy*; Malhotra, R., Ed.; Encyclopedia of Sustainability Science and Technology Series; Springer: Berlin/Heidelberg, Germany, 2020; pp. 503–517. [CrossRef]
48. Zhang, L.; Ovsepiyan, M.; Yuan, C. Supercritical carbon dioxide thickening for enhanced oil recovery: Methods, mechanisms, challenges, and outlook. *J. Mol. Liq.* **2025**, *417*, 126563. [CrossRef]
49. Lu, D.; Qu, F.; Zhang, C.; Guo, Y.; Luo, Z.; Xu, L.; Li, W. Innovative approaches, challenges, and future directions for utilizing carbon dioxide in sustainable concrete production. *J. Build. Eng.* **2024**, *97*, 110904. [CrossRef]
50. Wastewater Treatment Solutions for Oil Refineries: Conserving Water through Advanced Recycling & Reuse Technologies. Linde. Available online: <https://www.linde.com.cy/en/industries/refining/emission-abatement-and-control/water-treatment> (accessed on 10 October 2025).
51. Gastañadui-Cruz, J.C.; Reyes-Lopez, I.A.; Cortijo-Garcia, A.; Portilla-Rodriguez, H.R.; Bush, J.A.; Vanneste, J.; Garcia-Chevesich, P.A. Carbon Dioxide-Based Neutralization of High-Density Sludge Effluents as a Sustainable Climate and Water Quality Alternative to the Use of Strong Mineral Acids. *Sustainability* **2024**, *16*, 10363. [CrossRef]
52. Gulzar, A.; Gulzar, A.; Ansari, M.B.; He, F.; Gai, S.; Yang, P. Carbon dioxide utilization: A paradigm shift with CO₂ economy. *Chem. Eng. J. Adv.* **2020**, *3*, 100013. [CrossRef]
53. Pereira, L.B.; Sad, C.M.S.; Castro, E.V.R.; Filgueiras, P.E.; Lacerda, V. Environmental impacts related to drilling fluid waste and treatment methods: A critical review. *Fuel* **2022**, *310*, 122301. [CrossRef]
54. Hsiao, K.-Y.; Chung, R.-J.; Chen, C.-F.; Chang, P.-P.; Tsai, T.-H. Review on Supercritical Carbon Dioxide in Energy Storage Systems: Advances and Outlook. *Energy Fuels* **2025**, *39*, 12289–12308. [CrossRef]
55. Goepfert, A.; Czaun, M.; Jones, J.-P.; Surya Prakash, G.K.; Olah, G.A. Recycling of carbon dioxide to methanol and derived products—Closing the loop. *Chem. Soc. Rev.* **2014**, *43*, 7995–8048. [CrossRef] [PubMed]
56. Ramirez-Corredores, M.M. Sustainable production of CO₂-derived materials. *npj Mater. Sustain.* **2024**, *2*, 35. [CrossRef]
57. Boyce, J.; Sacchi, R.; Goetheer, E.; Steubing, B. A prospective life cycle assessment of global ammonia decarbonization scenarios. *Heliyon* **2024**, *10*, e27547. [CrossRef] [PubMed]
58. Kemp, T.J. Carbon Dioxide as a Polymer Feedstock. *Sci. Prog.* **2014**, *97*, 249–260. [CrossRef] [PubMed]
59. Net Zero Roadmap a Global Pathway to Keep the 1.5 °C Goal in Reach, 2023 Update. IEA. Available online: <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach> (accessed on 10 October 2025).
60. Essential Insights into CO₂ Refrigeration Technology. Refindustry. Available online: <https://refindustry.com/articles/techguides/essential-insights-into-co2-refrigeration-technology> (accessed on 15 October 2025).
61. He, T.; Zhou, Z.; Mao, N.; Qyyum, M.A. Transcritical CO₂ precooled single mixed refrigerant natural gas liquefaction process: Exergy and Exergoeconomic optimization. *Energy* **2024**, *294*, 130893. [CrossRef]
62. Bruno, F.; Belusko, M.; Halawa, E. CO₂ Refrigeration and Heat Pump Systems—A Comprehensive Review. *Energies* **2019**, *12*, 2959. [CrossRef]

63. Kochunni, S.K.; Chowdhury, K. Effect of precooling with transcritical CO₂ cycle on two types of LNG boil-off gas reliquefaction systems. *J. Nat. Gas Sci. Eng.* **2021**, *89*, 103876. [\[CrossRef\]](#)
64. Bi, Y.; Ju, Y. Design and analysis of CO₂ cryogenic separation process for the new LNG purification cold box. *Int. J. Refrig.* **2021**, *130*, 67–75. [\[CrossRef\]](#)
65. Kim, Y.; Lee, J.; An, N.; Kim, J. Advanced natural gas liquefaction and regasification processes: Liquefied natural gas supply chain with cryogenic carbon capture and storage. *Energy Convers. Manag.* **2023**, *292*, 117349. [\[CrossRef\]](#)
66. Pichugin, E.; Shenfeld, B. To the Issue of Differences of Drilling Sludge and Oil Sludge. *Ecol. Ind. Russ.* **2017**, *21*, 14–19. (In Russian) [\[CrossRef\]](#)
67. Darajah, M.H.; Karundeng, I.; Setiati, R.; Wastu, A.R.R. Drilling waste management using zero discharge technology with Drill Cutting Re-injection (DCRI) method for environmental preservation. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *802*, 012046. [\[CrossRef\]](#)
68. Onwukwe, S.I.; Nwakaudu, M.S. Drilling wastes generation and management approach. *Int. J. Environ. Sci. Dev.* **2012**, *3*, 252. [\[CrossRef\]](#)
69. Njuguna, J.; Siddique, S.; Kwroffie, L.B.; Piromrat, S.; Addae-Afoakwa, K.; Ekeh-Adegbotolu, U.; Oluyemi, G.; Yates, K.; Mishra, A.K.; Moller, L. The fate of waste drilling fluids from oil & gas industry activities in the exploration and production operations. *Waste Manag.* **2022**, *139*, 362–380. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Kazamias, G.; Zorpas, A.A. Drill cuttings waste management from oil and gas exploitation industries through end-of-waste criteria in the framework of circular economy strategy. *J. Clean. Prod.* **2021**, *322*, 129098. [\[CrossRef\]](#)
71. Carignan, M.-P.; Lake, C.B.; Menzies, T. Assessment of two thermally treated drill mud wastes for landfill containment applications. *Waste Manag. Res.* **2007**, *25*, 394–401. [\[CrossRef\]](#) [\[PubMed\]](#)
72. Phillips, L.; Morris, A.; Innes, G.; Clark, A.; Hinden, P.-M. Drilling Waste Management—Solutions that Optimize Drilling, Reduce Well Cost and Improve Environmental Performance. In Proceedings of the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, United Arab Emirates, 12–15 November 2018. [\[CrossRef\]](#)
73. Zhang, X.; Li, K.; Yao, A. Thermal Desorption Process Simulation and Effect Prediction of Oil-Based Cuttings. *ACS Omega* **2022**, *7*, 21675–21683. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Leonard, S.A.; Stegemann, J.A. Stabilization/solidification of petroleum drill cuttings: Leaching studies. *J. Hazard. Mater.* **2010**, *174*, 484–491. [\[CrossRef\]](#) [\[PubMed\]](#)
75. Tang, C.; Xie, S.X. Resource recovery and harmless treatment of waste oil-in-water drilling fluid. *Environ. Eng. Res.* **2017**, *22*, 277–280. [\[CrossRef\]](#)
76. Huang, Z.; Xu, Z.; Quan, Y.; Jia, H.; Li, J.; Li, Q.; Chen, Z.; Pu, K. A review of treatment methods for oil-based drill cuttings. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *170*, 022074. [\[CrossRef\]](#)
77. Rezaei Somee, M.; Shavandi, M.; Dastgheib, S.M.M.; Amoozegar, M.A. Bioremediation of oil-based drill cuttings by a halophilic consortium isolated from oil-contaminated saline soil. *3 Biotech* **2018**, *8*, 229. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Lebedev, A.; Cherepovitsyn, A. Waste Management during the Production Drilling Stage in the Oil and Gas Sector: A Feasibility Study. *Resources* **2024**, *13*, 26. [\[CrossRef\]](#)
79. Pugin, K.G.; Vlasov, A.S. Technology of use of drilling waste with a high content of hydrocarbons in road construction. *Transport. Transp. Facil. Ecol.* **2022**, *1*, 65–71. (In Russian)
80. Sharif, M.D.A.; Nagalakshmi, N.V.R.; Reddy, S.S.; Vasanth, G.; Uma Sankar, K. Drilling Waste Management and Control the Effects. *J. Adv. Chem. Eng.* **2017**, *7*, 166. [\[CrossRef\]](#)
81. Lebedev, A.P. Economic Efficiency of Drilling Cuttings Processing in the Oil and Gas Industry. Ph.D. Thesis, Saint Petersburg Mining University of Empress Catherine II, Saint Petersburg, Russia, 2024; p. 45. (In Russian)
82. Adegbotolu, U.V.; Njuguna, J.; Pollard, P.; Yates, K. Waste to Want: Polymer nanocomposites using nanoclays extracted from Oil based drilling mud waste. *IOP Conf. Ser. Mater. Sci. Eng.* **2014**, *64*, 012023. [\[CrossRef\]](#)
83. Pereira, L.B.; Sad, C.M.S.; da Silva, M.; Corona, R.R.B.; dos Santos, F.D.; Gonçalves, G.R.; Castro, E.V.R.; Filgueiras, P.R.; Lacerda, V. Oil Recovery from Water-Based Drilling Fluid Waste. *Fuel* **2019**, *237*, 335–343. [\[CrossRef\]](#)
84. Jagaba, A.H.; Kutty, S.R.M.; Lawal, I.M.; Birniwa, A.H.; Affam, A.C.; Yaro, N.S.A.; Usman, A.K.; Umaru, I.; Abubakar, S.; Noor, A.; et al. Circular economy potential and contributions of petroleum industry sludge utilization to environmental sustainability through engineered processes—A review. *Clean. Circ. Bioecon.* **2022**, *3*, 100029. [\[CrossRef\]](#)
85. Ahmad, J. Bioremediation of petroleum sludge using effective microorganism (EM) technology. *Pet. Sci. Technol.* **2017**, *35*, 1515–1522. [\[CrossRef\]](#)
86. Hui, K.; Tang, J.; Lu, H.; Xi, B.; Qu, C.; Li, J. Status and prospect of oil recovery from oily sludge: A review. *Arab. J. Chem.* **2020**, *13*, 6523–6543. [\[CrossRef\]](#)
87. Zhang, J.; Li, J.; Thring, R.W.; Hu, X.; Song, X. Oil recovery from refinery oily sludge via ultrasound and freeze/thaw. *J. Hazard. Mater.* **2012**, *204*, 195–203. [\[CrossRef\]](#) [\[PubMed\]](#)

88. Hu, G.; Li, J.; Zeng, G. Recent development in the treatment of oily sludge from petroleum industry: A review. *J. Hazard. Mater.* **2013**, *261*, 70–90. [CrossRef] [PubMed]
89. Su, B.; Huang, L.; Li, S.; Ding, L.; Liu, B.; Zhang, A. Chemical–microwave–ultrasonic compound conditioning treatment of highly-emulsified oily sludge in gas fields. *Nat. Gas Ind. B* **2019**, *6*, 412–418. [CrossRef]
90. Guo, H.; Feng, S.; Jiang, J.; Zhang, M.; Lin, H.; Zhou, X. Application of Fenton’s reagent combined with sawdust on the dewaterability of oily sludge. *Environ. Sci. Pollut. Res.* **2014**, *21*, 10706–10712. [CrossRef] [PubMed]
91. Khanpour, R.; Sheikhi-Kouhsar, M.R.S.; Esmailzadeh, F.; Mowla, D. Removal of contaminants from polluted drilling mud using supercritical carbon dioxide extraction. *J. Supercrit. Fluids* **2014**, *88*, 1–7. [CrossRef]
92. State Report “On the state and use of mineral resources of the Russian Federation in 2022”. Ministry of Natural Resources and Environment of the Russian Federation. Federal Agency for Mineral Resources. Available online: https://mnr.gov.ru/docs/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/gosudarstvennyy_doklad_o_sostoyanii_i_ispolzovani_mineralno_syrevykh_resursov_rossiyskoy_federatsii/ (accessed on 20 September 2025). (In Russian)
93. Bahadori, A. *Fundamentals of Enhanced Oil and Gas Recovery from Conventional and Unconventional Reservoirs*; Gulf Professional Publishing: Cambridge, MA, USA, 2018. [CrossRef]
94. Malozyomov, B.V.; Martyushev, N.V.; Kukartsev, V.V.; Tynchenko, V.S.; Bukhtoyarov, V.V.; Wu, X.; Tyncheko, Y.A.; Kukartsev, V.A. Overview of Methods for Enhanced Oil Recovery from Conventional and Unconventional Reservoirs. *Energies* **2023**, *16*, 4907. [CrossRef]
95. Cheraghi, Y.; Kord, S.; Mashayekhizadeh, V. Application of Machine Learning Techniques for Selecting the Most Suitable Enhanced Oil Recovery Method; Challenges and Opportunities. *J. Pet. Sci. Eng.* **2021**, *205*, 108761. [CrossRef]
96. Khudaiberdiev, A.; Kosianov, P. Integrated physical enhanced recovery method for high-viscosity oil reservoirs. *E3S Web Conf.* **2021**, *244*, 09012. [CrossRef]
97. Alsalem, F.; Thiemann, T. Produced Water from the Oil and Gas Industry as a Resource—South Kuwait as a Case Study. *Resources* **2024**, *13*, 118. [CrossRef]
98. Ma, X.; He, D.; Wei, Y.; Guo, J.; Jia, C. Enhanced gas recovery: Theory, technology, and prospects. *Nat. Gas Ind. B* **2023**, *10*, 393–405. [CrossRef]
99. Ping, G.; Shasha, J.; Caizhen, P. Technologies and countermeasures for gas recovery enhancement. *Nat. Gas Ind. B* **2014**, *1*, 96–102. [CrossRef]
100. Rahaman, M.S.; Islam, M.A. Integrating CO₂ sequestration and enhanced gas recovery: A comprehensive evaluation for sustainable carbon management. *J. Petrol. Explor. Prod. Technol.* **2025**, *15*, 160. [CrossRef]
101. Iddphonce, R.; Wang, J.; Zhao, L. Review of CO₂ injection techniques for enhanced shale gas recovery: Prospect and challenges. *J. Nat. Gas Sci. Eng.* **2020**, *77*, 103240. [CrossRef]
102. Sambo, C.; Liu, N.; Shaibu, R.; Ahmed, A.A.; Hashish, R.G. A Technical Review of CO₂ for Enhanced Oil Recovery in Unconventional Oil Reservoirs. *Geoenergy Sci. Eng.* **2023**, *221*, 111185. [CrossRef]
103. Cooper, C.M.; McCall, J.; Stokes, S.C.; McKay, C.; Bentley, M.J.; Rosenblum, J.S.; Blewett, T.A.; Huang, Z.; Miara, A.; Talmadge, M.; et al. Oil and Gas Produced Water Reuse: Opportunities, Treatment Needs, and Challenges. *ACS ES&T Eng.* **2022**, *2*, 347–366. [CrossRef]
104. Zolghadr, E.; Firouzjaei, M.D.; Amouzandeh, G.; LeClair, P.; Elliott, M. The Role of Membrane-Based Technologies in Environmental Treatment and Reuse of Produced Water. *Front. Environ. Sci.* **2021**, *9*, 629767. [CrossRef]
105. Coelho, A.; Castro, A.V.; Dezotti, M.; Sant’Anna, G.L., Jr. Treatment of petroleum refinery sourwater by advanced oxidation processes. *J. Hazard. Mater.* **2006**, *137*, 178–184. [CrossRef] [PubMed]
106. Jafarinejad, S.; Jiang, S.C. Current technologies and future directions for treating petroleum refineries and petrochemical plants (PRPP) wastewaters. *J. Environ. Chem. Eng.* **2019**, *7*, 103326. [CrossRef]
107. Al-Ajmi, F.; Al-Marri, M.; Almomani, F.; AlNouss, A. A Comprehensive Review of Advanced Treatment Technologies for the Enhanced Reuse of Produced Water. *Water* **2024**, *16*, 3306. [CrossRef]
108. Guo, H.; Qin, Q.; Hu, M.; Chang, J.-S.; Lee, D.-J. Treatment of refinery wastewater: Current status and prospects. *J. Environ. Chem. Eng.* **2024**, *12*, 112508. [CrossRef]
109. Karkou, E.; Papadaki, A.; Angelis-Dimakis, A.; Arnaldos, A.N.; Arampatzis, G. Water efficiency solutions for the oil refinery industry. *J. Environ. Manag.* **2025**, *391*, 126343. [CrossRef] [PubMed]
110. Jafarinejad, S. 6—Treatment of Oily Wastewater. In *Petroleum Waste Treatment and Pollution Control*; Jafarinejad, S., Ed.; Butterworth-Heinemann: Oxford, UK, 2017; pp. 185–267. [CrossRef]
111. El-Naas, M.H.; Alhajja, M.A.; Al-Zuhair, S. Evaluation of a three-step process for the treatment of petroleum refinery wastewater. *J. Environ. Chem. Eng.* **2014**, *2*, 56–62. [CrossRef]
112. Fetanat, A.; Tayebi, M. A picture fuzzy set-based decision support system for treatment technologies prioritization of petroleum refinery effluents: A circular water economy transition towards oil & gas industry. *Sep. Purif. Technol.* **2022**, *303*, 122220. [CrossRef]

113. Meijer, D.; Madin, C. Removal of dissolved and dispersed hydrocarbons from oil and gas produced water with Macro Porous Polymer Extraction technology to reduce toxicity and allow water reuse. *APPEA J.* **2010**, *50*, 637. [\[CrossRef\]](#)
114. Sarrafzadeh, M.-H. Chapter 16—Circular economy in petroleum industries: Implementing Water Closed Loop System. In *Petroleum Industry Wastewater. Advanced and Sustainable Treatment Methods*; El-Naas, M.H., Banerjee, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 249–262. [\[CrossRef\]](#)
115. Ahmadun, F.-R.; Pendashteh, A.; Abdullah, L.C.; Biak, D.R.A.; Madaeni, S.S.; Abidin, Z.Z. Review of technologies for oil and gas produced water treatment. *J. Hazard. Mater.* **2009**, *170*, 530–551. [\[CrossRef\]](#) [\[PubMed\]](#)
116. Ranade, V.V.; Bhandari, V.M. Chapter 1—Industrial Wastewater Treatment, Recycling, and Reuse: An Overview. In *Industrial Wastewater Treatment, Recycling, and Reuse*; Ranade, V.V., Bhandari, V.M., Eds.; Butterworth-Heinemann: Oxford, UK, 2014; pp. 1–80. [\[CrossRef\]](#)
117. Igunnu, E.T.; Chen, G.Z. Produced water treatment technologies. *Int. J. Low-Carbon. Technol.* **2014**, *9*, 157–177. [\[CrossRef\]](#)
118. Khatoun, R.; Raksasat, R.; Ho, Y.C.; Lim, J.W.; Jumbri, K.; Ho, C.-D.; Chan, Y.J.; Abdelfattah, E.A.; Khoo, K.S. Reviewing Advanced Treatment of Hydrocarbon-Contaminated Oilfield-Produced Water with Recovery of Lithium. *Sustainability* **2023**, *15*, 16016. [\[CrossRef\]](#)
119. Bandaletova, A.A.; Gavrilov, A.Y.; Galin, E.V. Lithium extraction from associated waters on the example of Orenburg OGCF. *PRoneft. Prof. About Oil* **2021**, *6*, 29–32. (In Russian) [\[CrossRef\]](#)
120. Yelatontsev, D.; Mukhachev, A.; Shevchenko, V. Comprehensive utilization of mineral resources in produced water from oil and gas industry—A critical review. *Desalination* **2026**, *619*, 119558. [\[CrossRef\]](#)
121. Socio-Economic Situation of Russia (January–July 2024). Federal State Statistics Service (Rosstat). Available online: <https://rosstat.gov.ru/storage/mediabank/osn-07-2024.pdf> (accessed on 1 January 2026). (In Russian)
122. Akhmetov, S.A. *Deep Oil and Gas Refining Technology*; Gilem: Ufa, Russia, 2022; pp. 622–638. (In Russian)
123. Glagoleva, O.F.; Kapustin, V.M. Improving the Efficiency of Oil Treating and Refining Processes (Review). *Pet. Chem.* **2020**, *60*, 1207–1215. [\[CrossRef\]](#)
124. Robinson, P.R.; Dolbear, G.E. Hydrocracking. In *Springer Handbook of Petroleum Technology*; Hsu, C.S., Robinson, P.R., Eds.; Springer: Cham, Switzerland, 2017; pp. 713–776. [\[CrossRef\]](#)
125. Bingham, F.E.; Nelson, D.E.; Morton, D. Hydroprocessing Reactor Internals. In *Springer Handbook of Petroleum Technology*; Hsu, C.S., Robinson, P.R., Eds.; Springer: Cham, Switzerland, 2017; pp. 777–786. [\[CrossRef\]](#)
126. Fahim, M.A.; Alsahhaf, T.A.; Elkilani, A. Chapter 13—Residue Upgrading. In *Fundamentals of Petroleum Refining*; Fahim, M.A., Alsahhaf, T.A., Elkilani, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2010; pp. 325–355. [\[CrossRef\]](#)
127. Bellussi, G.; Rispoli, G.; Landoni, A.; Millini, R.; Molinari, D.; Montanari, E.; Moscotti, D.; Pollesel, P. Hydroconversion of heavy residues in slurry reactors: Developments and perspectives. *J. Catal.* **2013**, *308*, 189–200. [\[CrossRef\]](#)
128. Khadzhiev, S.N.; Kadiev, K.M.; Kadieva, M.K. Synthesis and properties of nanosized systems as efficient catalysts for hydroconversion of heavy petroleum feedstock. *Pet. Chem.* **2014**, *54*, 323–346. [\[CrossRef\]](#)
129. Kadiev, K.; Maximov, A.L.; Ancheyta, J. Novel Technologies for Upgrading Heavy and Extra-Heavy Oil. In *Catalytic In-Situ Upgrading of Heavy and Extra-Heavy Crude Oils*; Ancheyta, J., Varfolomeev, M., Yuan, C., Eds.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2023; pp. 489–520. [\[CrossRef\]](#)
130. Kadiev, K.M.; Gyul'maliev, A.M.; Zekel', L.A.; Kadieva, M.K.; Dandaev, A.U.; Batov, A.E.; Visaliev, M.Y. Hydroconversion of Vacuum Residue of a Blend of Western Siberian Oils in the Presence of Ex Situ Synthesized Suspensions of Nanosized Catalysts. *Pet. Chem.* **2019**, *59*, S37–S44. [\[CrossRef\]](#)
131. Kadiev, K.M.; Shpirt, M.Y.; Visaliev, M.Y.; Kadieva, M.K.; Kubrin, N.A. Features of Heavy Hydrocarbon Feedstock Hydroconversion in the Presence of a Suspended Nanosized Catalyst. *Pet. Chem.* **2018**, *58*, 1181–1185. [\[CrossRef\]](#)
132. Liu, Y.; Gao, L.; Wen, L.; Zong, B. Recent Advances in Heavy Oil Hydroprocessing Technologies. *Recent Pat. Chem. Eng.* **2009**, *2*, 22–36. [\[CrossRef\]](#)
133. Paukov, A.; Magaril, R.; Magaril, E. An Investigation of the Feasibility of the Organic Municipal Solid Waste Processing by Coking. *Sustainability* **2019**, *11*, 389. [\[CrossRef\]](#)
134. Sun, X.; Liang, X. Influence of Different Fuels Physical Properties for Marine Diesel Engine. *Energy Procedia* **2017**, *142*, 1159–1165. [\[CrossRef\]](#)
135. Ramirez-Corredores, M.M. *The Science and Technology of Unconventional Oils: Finding Refining Opportunities*, 1st ed.; Academic Press: Cambridge, MA, USA, 2017.
136. Kapadia, P.R.; Wang, J.J.; Kallos, M.S.; Gates, I.D. Practical process design for in situ gasification of bitumen. *Appl. Energy* **2013**, *107*, 281–296. [\[CrossRef\]](#)
137. Kurochkin, A.K.; Galikhametov, R.N.; Kurochkin, A.A. Strategy of high profitability of bituminous oil deposits. *Sphera. Oil Gas* **2020**, *1*, 46–57. (In Russian)

138. Khusnutdinov, I.S.; Kozin, V.G.; Diyarov, I.N. Process for Fractionation of Highly Viscous Raw Material. RU Patent RU2055858C. 10 March 1996. Available online: <https://patents.google.com/patent/RU2055858C1/en#citedBy> (accessed on 1 January 2026). (In Russian)
139. Gray, M.R. *Upgrading Oilsands Bitumen and Heavy Oil*; University of Alberta Press: Edmonton, KY, USA, 2015.
140. Zhao, F.; Liu, Y.; Lu, N.; Xu, T.; Zhu, G.; Wang, K. A review on upgrading and viscosity reduction of heavy oil and bitumen by underground catalytic cracking. *Energy Rep.* **2021**, *7*, 4249–4272. [\[CrossRef\]](#)
141. Chauhan, G.; de Klerk, A. Extraction of Vanadium and Nickel from Diluted Bitumen and Partially Deasphalted Oil Using Ionic Liquids. *Energy Fuel* **2020**, *34*, 10849–10857. [\[CrossRef\]](#)
142. Petrov, S.M.; Kayukova, G.P.; Goncharova, I.N.; Safiulina, A.G.; Lakhova, A.I. High-quality asphalt binders produced by deasphalting of natural bitumen. In Proceedings of the International Multidisciplinary Scientific GeoConference: SGEM, Albena, Bulgaria, 2–8 July 2018. [\[CrossRef\]](#)
143. Yeo, L.S.; Tiang, C.W.P.; Teng, S.Y.; Ng, W.P.Q.; Lim, C.H.; Leong, W.D.; Lam, H.L.; Sunarso, J.; How, B.S. Rethinking circularity with Re-refineries and supply chains reintegration via multi-objective pareto graph theoretical approach. *Energy* **2023**, *279*, 127814. [\[CrossRef\]](#)
144. Hsu, Y.L.; Liu, C.C. Evaluation and selection of regeneration of waste lubricating oil technology. *Environ. Monit. Assess.* **2011**, *176*, 197–212. [\[CrossRef\]](#) [\[PubMed\]](#)
145. Vural, U.S. Waste mineral oils re-refining with physicochemical methods. *Turk. J. Eng.* **2020**, *4*, 62–69. [\[CrossRef\]](#)
146. Saleem, H.J.; Karim, A.R. Re-refining of used lubricating oil by vacuum distillation/thin wiped film evaporation technique. *Pet. Sci. Technol.* **2020**, *38*, 323–330. [\[CrossRef\]](#)
147. Oladimeji, T.E.; Sonibare, J.A.; Omoleye, J.A.; Adegbola, A.A.; Okagbue, H.I. Data on the treatment of used lubricating oil from two different sources using solvent extraction and adsorption. *Data Brief.* **2018**, *19*, 2240–2252. [\[CrossRef\]](#) [\[PubMed\]](#)
148. Osman, D.I.; Attia, S.K.; Taman, A.R. Recycling of used engine oil by different solvent. *Egypt. J. Pet.* **2018**, *27*, 221–225. [\[CrossRef\]](#)
149. Cao, Y.; Yan, F.; Li, J.; Liang, X.; He, B. Used lubricating oil recycling using a membrane filtration: Analysis of efficiency, structural and composing. *Desalin. Water Treat.* **2009**, *11*, 73–80. [\[CrossRef\]](#)
150. Widodo, S.; Khoiruddin, K.; Ariono, D.; Subagio, S.; Wenten, I.G. Re-refining of waste engine oil using ultrafiltration membrane. *J. Environ. Chem. Eng.* **2020**, *8*, 103789. [\[CrossRef\]](#)
151. Klenert, D.; García-Gutiérrez, P.; Tonini, D.; Saveyn, H.; Marschinski, R. The economics of waste oil recycling in the EU. *J. Environ. Econ. Policy* **2025**, *14*, 1–22. [\[CrossRef\]](#)
152. Audibert, F. Chapter 6. Alternative valorization routes (refinery, cogeneration, and rerefining residue). In *Waste Engine Oils: Rerefining and Energy Recovery*; Audibert, F., Ed.; Elsevier: Amsterdam, The Netherlands, 2006; pp. 247–269. [\[CrossRef\]](#)
153. Gangar, N.; Macchietto, S.; Markides, C.N. Recovery and Utilization of Low-Grade Waste Heat in the Oil-Refining Industry Using Heat Engines and Heat Pumps: An International Technoeconomic Comparison. *Energies* **2020**, *13*, 2560. [\[CrossRef\]](#)
154. Akhtar, M.S.; Ali, S.; Zaman, W. Recent Advancements in Catalysts for Petroleum Refining. *Catalysts* **2024**, *14*, 841. [\[CrossRef\]](#)
155. Pham, P.T.H.; Pham, C.Q.; Dam, T.-T.; Nguyen, Q.-A.; Nguyen, T.M. A comprehensive review of catalyst deactivation and regeneration in heavy oil hydroprocessing. *Fuel Process. Technol.* **2025**, *267*, 108170. [\[CrossRef\]](#)
156. Anekwe, I.M.S.; Isa, Y.M. Unlocking catalytic longevity: A critical review of catalyst deactivation pathways and regeneration technologies. *Energy Adv.* **2025**, *4*, 1075–1113. [\[CrossRef\]](#)
157. Bartholomew, C.H.; Argyle, M.D. Advances in Catalyst Deactivation and Regeneration. *Catalysts* **2015**, *5*, 949–954. [\[CrossRef\]](#)
158. Golubev, A.B. Increased economic efficiency of oil refineries as a result of the use of “ex-situ” hydroprocess catalyst regeneration. *Sphere. Oil Gas* **2023**, *2*, 36–38. (In Russian)
159. Ferella, F.; Innocenzi, V.; Maggiore, F. Oil refining spent catalysts: A review of possible recycling technologies. *Resour. Conserv. Recycl.* **2016**, *108*, 10–20. [\[CrossRef\]](#)
160. Marafi, M.; Rana, M.S. Refinery waste: The spent hydroprocessing catalyst and its recycling options. *WIT Trans. Ecol. Environ.* **2016**, *202*, 219–230. [\[CrossRef\]](#)
161. Al-Sheeha, H.; Marafi, M.; Raghavan, V.; Rana, M.S. Recycling and Recovery Routes for Spent Hydroprocessing Catalyst Waste. *Ind. Eng. Chem. Res.* **2013**, *52*, 12794–12801. [\[CrossRef\]](#)
162. Liang, X.; Tang, J.; Li, L.; Wu, Y.; Sun, Y. A review of metallurgical processes and purification techniques for recovering Mo, V, Ni, Co, Al from spent catalysts. *J. Clean. Prod.* **2022**, *376*, 134108. [\[CrossRef\]](#)
163. Gumerov, F.M.; Neindre, B.L.; Bilalov, T.R.; Sagdeev, A.A. Regeneration of Spent Catalyst and Impregnation of Catalyst by Supercritical Fluid. *Int. J. Anal. Mass. Spectrom. Chromatogr.* **2016**, *4*, 51–65. [\[CrossRef\]](#)
164. Iodis, V.A. Activation, regeneration and recycling of spent catalyst using ultrasonic impact. *Mine Surv. Subsurf. Use* **2025**, *25*, 61–65. (In Russian) [\[CrossRef\]](#)
165. Karim, S.; Ting, Y.P. Recycling pathways for platinum group metals from spent automotive catalyst: A review on conventional approaches and bio-processes. *Resour. Conserv. Recycl.* **2021**, *170*, 105588. [\[CrossRef\]](#)

166. Asghari, I.; Mousavi, S.M.; Amiri, F.; Tavassoli, S. Bioleaching of spent refinery catalysts: A review. *J. Ind. Eng. Chem.* **2013**, *19*, 1069–1081. [CrossRef]
167. Schmitt, R. FCC catalyst finds three safe reuse outlets in Europe. *Oil Gas J.* **1991**, *89*, 101–102.
168. Gameiro, T.; Costa, C.; Labrincha, J.; Novais, R.M. Reusing spent fluid catalytic cracking catalyst as an adsorbent in wastewater treatment applications. *Mater. Today Sustain.* **2023**, *24*, 100555. [CrossRef]
169. Gureev, A.A.; Azev, V.S. *Automobile Gasoline. Properties and Applications*; Neft' i Gaz: Moscow, Russia, 1996; pp. 139–145.
170. Makushev, U.P.; Ryndin, V.V. Storage of mineral oil and decrease in their losses. *Sci. Technol. Kazakhstan* **2011**, *3*, 49–60. (In Russian)
171. Pshenin, V.V. Determination of Parameters of Rational Placement of Oil and Petroleum Product Vapor Recovery Unit. *Int. J. Eng. Trans. B Appl.* **2025**, *38*, 362–367. [CrossRef]
172. Vapor Recovery Units (VRU). Control Emissions and Recover Valuable Hydrocarbons. Available online: <https://www.zeeco.com/products/vapor-recovery-units> (accessed on 20 December 2025).
173. Vapor Recovery During Railcar Loading. Petrogas Systems. Available online: <https://petrogassystems.com/technology/vapor-recoveryrailcar-loading/> (accessed on 20 December 2025).
174. El-Samanody, M.; Ghorab, A.; Noaman, A.S. Design and study of floating roofs for oil storage tanks. *Mech. Mech. Eng.* **2017**, *21*, 117–136.
175. Man, H.; Shao, X.; Cai, W.; Wang, K.; Cai, Z.; Xue, M.; Liu, H. Utilizing a optimized method for evaluating vapor recovery equipment control efficiency and estimating evaporative VOC emissions from urban oil depots via an extensive survey. *J. Hazard. Mater.* **2024**, *479*, 135710. [CrossRef] [PubMed]
176. Batić, I.M. Reduction of evaporation losses in oil and oil derivatives storage tanks: A case study for warehouse in Požega, Serbia. *Therm. Sci.* **2023**, *27*, 2455–2464. [CrossRef]
177. Magaril, E.; Magaril, R. Impact of surfactants in micro concentrations on certain properties of organic liquids as a basis for improving some oil-and-gas industry processes and properties of gasoline. *Colloids Surf. A* **2017**, *529*, 733–738. [CrossRef]
178. Magaril, E.; Magaril, R. Improving the environmental and performance characteristics of vehicles by introducing the surfactant additive into gasoline. *Environ. Sci. Pollut. Res.* **2016**, *23*, 17049–17057. [CrossRef] [PubMed]
179. Magaril, E. Reducing gasoline loss from evaporation by the introduction of a surface-active fuel additive. *WIT Trans. Built Environ.* **2015**, *146*, 233–242. [CrossRef]
180. Beiranvand, F.; Najibi, H. Decrease in evaporative loss of volatile fuels using new mixture of surfactants. *Pet. Sci. Technol.* **2021**, *39*, 1139–1156. [CrossRef]
181. Khalidov, I.; Milovidov, K.; Soltakhanov, A. Decommissioning of oil and gas assets: Industrial and environmental security management, international experience and Russian practice. *Heliyon* **2021**, *7*, e07646. [CrossRef] [PubMed]
182. Ghi, T.; Mulyo, P.; Fazal, I.S.; Chhapparwal, H.; Das, A. Oil & Gas Asset Decommissioning Decision-Making. Achieving Net Zero & Energy Security. Arthur D. Little 2025. Available online: <https://www.adlittle.com/en/insights/viewpoints/oil-gas-asset-decommissioning-decision-making> (accessed on 20 February 2026).
183. The Circular Economy: An Innovative Path to Sustainability in Oil and Gas. GEP. 2019. Available online: <https://www.gep.com/blog/mind/the-circular-economy-an-innovative-path-to-sustainability-in-oil-and-gas> (accessed on 5 September 2025).
184. Velenturf, A.P.M. Circular Oil & Gas Decommissioning: The Social, Economic, Technical and Environmental Values of North Sea Oil & Gas Decommissioning for Local Communities and Companies. University of Leeds. 2020. Available online: https://www.researchgate.net/publication/347530402_Circular_Oil_Gas_Decommissioning_The_social_economic_technical_and_environmental_values_of_North_Sea_oil_gas_decommissioning_for_local_communities_and_companies (accessed on 19 October 2025).
185. Invernizzi, D.C.; Locatelli, G.; Velenturf, A.; Love, P.E.D.; Purnell, P.; Brookes, N.J. Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning. *Energy Policy* **2020**, *144*, 111677. [CrossRef]
186. Mignacca, B.; Locatelli, G.; Velenturf, A. Modularisation as enabler of circular economy in energy infrastructure. *Energy Policy* **2020**, *139*, 111371. [CrossRef]
187. Tashtamirov, M. Environmental Consequences and Remediation Strategies for Abandoned Oil and Gas Infrastructure. *BIO Web Conf.* **2023**, *63*, 03011. [CrossRef]
188. Okoli, C.; Pawlowski, S.D. The Delphi method as a research tool: An example, design considerations and applications. *Inf. Manag.* **2004**, *42*, 15–29. [CrossRef]
189. Mohammed, S.; Desha, C.; Goonetilleke, A. Investigating the potential of low-carbon pathways for hydrocarbon-dependent rentier states: Sociotechnical transition in Qatar. *Technol. Forecast. Soc. Change* **2023**, *189*, 122337. [CrossRef]
190. Zhang, P.; Ma, S.-G.; Zhao, Y.-N.; Cao, X.-Y. Analyzing Core Competencies and Correlation Paths of Emerging Engineering Talent in the Construction Industry—An Integrated ISM–MICMAC Approach. *Sustainability* **2023**, *15*, 16011. [CrossRef]
191. Hasson, F.; Keeney, S.; McKenna, H. Revisiting the Delphi technique—Research thinking and practice: A discussion paper. *Int. J. Nurs. Stud.* **2025**, *168*, 105119. [CrossRef] [PubMed]

192. Ghosh, A.; Choudhury, S. Understanding different types of review articles: A primer for early career researchers. *Indian J. Psychiatry* **2025**, *67*, 535–541. [[CrossRef](#)] [[PubMed](#)]
193. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [[CrossRef](#)]
194. Sarkar, S.; Bhatia, G. Writing and appraising narrative reviews. *J. Clin. Sci. Res.* **2021**, *10*, 169–172. [[CrossRef](#)] [[PubMed](#)]
195. Only 25% of the 2 Million Tons of Used Lubricating Oils are Collected for Recycling in RUSSIA. Russian Environmental Operator (REO). 2023. Available online: <https://reo.ru/tpost/mi3mjh88l1-reo-lish-25-ot-2-mln-tonn-otrabotannih-s> (accessed on 12 November 2025).
196. GEIR Position on the Revision of the Waste Framework Directive. GEIR. 2024. Available online: https://www.geir-rerefining.org/wp-content/uploads/2024/04/GEIR-position-paper_Waste-Framework-Directive.pdf (accessed on 7 November 2025).
197. Spent Catalyst Recycling Market Analysis. 2026. Available online: <https://www.cognitivemarketresearch.com/spent-catalyst-recycling-market-report> (accessed on 10 December 2025).
198. The Volume of the Vapor Recovery Units Market—By Technology, by Application, by End-Use, Growth Forecast for 2025–2034. Global Market Insights. Available online: <https://www.gminsights.com/ru/industry-analysis/vapor-recovery-units-market> (accessed on 20 December 2025).
199. Sellitto, M.A.; De Lima, M.S.; Da Silva, L.T.; Kadel, N., Jr.; Butturi, M.A. Decision support criteria for the implementation of waste-to-energy conversion systems: A case study in Southern Brazil. *Benchmarking Int. J.* **2025**, *32*, 1267–1283. [[CrossRef](#)]

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