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Co-Exploration: A Strategy for Integrating Alternative Geosciences Resources for the Petroleum Industry in an Energy Transition Context

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Abstract

This study proposes the concept of Co-exploration as a diversification strategy that enables oil and gas (O&G) companies to leverage their geoscientific capabilities to jointly assess multiple resources, such as geothermal energy, natural hydrogen, lithium in brines, geological storage, and deep-sea mining. Those resources share a reliance on traditional upstream capabilities, including geological mapping, geophysical data acquisition and interpretation, reservoir characterization, modeling techniques, risk analysis, drilling, operations in remote environments, and the management of complex projects. A compatibility matrix was developed to summarize how well these alternatives fit a Co-exploration strategy. Alternatives such as CCS and CO_2-EOR stand out for their technical and operational synergies with O&G upstream operations; however, they rely on tax incentives and an immature carbon market. Conversely, geothermal energy (EGS) and lithium production from brines represent more balanced alternatives for a Co-exploration strategy, combining geoscientific synergies, environmental and climate compatibility. Natural hydrogen offers strong strategic alignment but faces low technological maturity and market uncertainties. Finally, deep-sea mining emerges as the least viable alternative, despite its strategic appeal regarding the supply of critical elements. However, applying legacy O&G methods and tools to these alternative resources is not straightforward. Alternative projects can differ from O&G projects in investment scale, time horizons, and risk–return profiles. There are also challenges associated with permitting, resource ownership, environmental and monitoring requirements, long-term liabilities, and social acceptance.

Keywords: co-exploration; energy transition; upstream; alternative resources; geothermal energy; natural hydrogen; geosciences; portfolio diversification; risk management

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1. Introduction

The transition to a low-emission energy system, driven by the urgency to mitigate climate change and achieve net-zero emissions targets, poses unprecedented challenges to the oil and gas (O&G) industry, particularly to its Exploration and Production (E&P) segment [1]. Traditionally, O&G Exploration operates under a risk framework dominated by geological uncertainties, price volatility, and technical–operational challenges [2]. However, the dynamics of the energy transition introduce new layers of complexity and systemic

uncertainty: risks, previously concentrated on technical and market factors, are increasingly shaped by the evolution of climate policies, investor expectations, social pressure, decarbonization imperatives, and volatility in long-term demand estimates.

Capital intensity, long investment cycles, and carbon exposure make exploratory projects especially vulnerable to unpredictable future scenarios. Figure 1 illustrates the volatility and divergence of global oil demand projections estimated and published by the Organization of the Petroleum Exporting Countries (OPEC) and the International Energy Agency (IEA) between 2015 and 2025. Rather than representing a simple evolution of forecasts that converge toward consensus over time, the figure reveals persistent and widening disagreement between two major institutional perspectives, reflecting fundamentally different assumptions about policy stringency, technological change, and societal responses to climate imperatives. OPEC scenarios generally assume continued economic growth with moderate efficiency improvements and limited policy intervention, projecting demand growth or stabilization through mid-century [3–13]. IEA scenarios, conversely, explicitly model varying degrees of policy ambition, from Stated Policies (STEPS) to announced pledges to Net-Zero Emissions by 2050 (NZE), resulting in a wide range from continued growth to sharp decline [14–24]. The spread between these scenarios has widened post-2020, particularly as climate commitments have intensified.

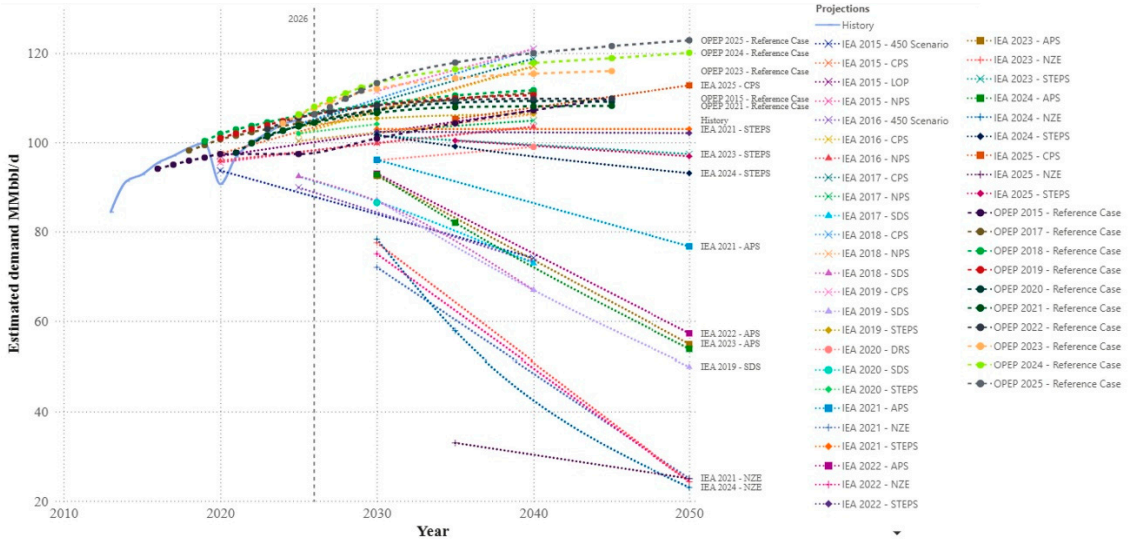


Figure 1. Global oil demand projections published by OPEC and the IEA between 2015 and 2025. The figure illustrates different analytical frameworks: IEA scenarios reflect varying levels of policy ambition and technological deployment aligned with climate targets (from STEPS to NZE), while OPEC projections reflect baseline economic growth assumptions with limited policy intervention. The divergence between institutions and the intertemporal variability within each institution's projections reflect deep uncertainty regarding energy transition pace, policy effectiveness, technological disruption, and behavioural changes. Source: Authors' elaboration based on data from OPEC [3–13] and the IEA [14–24].

This dispersion reflects the deep uncertainty about the energy sector's future and highlights the challenge of long-term planning for capital-intensive upstream projects with decades-long cycles. The consequence is an expansion of the decision-making uncertainty space, with direct impacts on exploration portfolio design, risk appetite, investment horizons, and the need for strategic options that offer flexibility and resilience.

Faced with this landscape, O&G companies have sought responses through different strategies that include: increased efficiency and reduction in operational greenhouse gas (GHG) emissions [25,26]; portfolio reconfiguration prioritizing assets with lower breakeven

points, shorter investment cycles, and lower carbon intensity [27–29]; and expansion into low-carbon businesses through the development of capabilities in renewable energy, CO_2 capture and storage, biofuels, and hydrogen production by electrolysis [30–32].

However, these diversification alternatives present significant limitations. Most transition strategies adopted by O&G companies tend to move away from the technical–organizational core of E&P, requiring new capabilities, creation of distinct value chains, and risk–return profiles that do not align with the consolidated geological exploration competencies [33]. Additionally, such strategies frequently position exploration as an activity to be gradually reduced, relegating the upstream segment to a rearguard role in the transition process [27,30,34–36].

This strategic movement, although apparently aligned with climate imperatives, may be premature and even counterproductive. Even under scenarios of accelerated energy transition, traditional O&G exploratory activity will remain necessary in the short and medium term, given the imperatives of energy security, the natural decline of producing fields, geopolitical volatility, and the need for selective replacement of low-cost, low-risk reserves [37,38]. Moreover, premature abandonment of Exploration may compromise not only companies' operational resilience, but also decades of investment in developing geoscientific competencies, data assets, and exploratory infrastructure.

Conceptual Gap and Study Motivation

The literature on energy transition strategies in the O&G industry focuses predominantly on two poles: (i) optimization and decarbonization of the fossil fuel core business [25,26] and (ii) radical diversification into low-carbon sectors dissociated from upstream operations, such as wind and solar renewables [30–32]. However, a conceptual and strategic gap exists, since little attention has been given to how consolidated Exploration competencies and assets can be reoriented and expanded to assess and develop alternative subsurface resources, creating strategic optionality without abandoning the technical core of E&P.

Indeed, the geoscientific competencies accumulated by the O&G industry, including capabilities in acquisition and interpretation of seismic and geophysical data, reservoir modeling, deep-well drilling, geological risk management, and operation in complex environments, are directly transferable to the exploration of a variety of subsurface resources beyond hydrocarbons, such as geothermal energy, natural hydrogen, lithium in brines, submarine mining, and geological storage [33,39,40]. This transferability opens the possibility of an integrated diversification strategy that does not require creating new value chains from scratch, but instead leverages existing technical–operational synergies and infrastructure to expand the range of opportunities to monetize geological knowledge.

Despite this potential synergy, the literature lacks conceptual frameworks structuring how this integration can be implemented systematically. Concepts such as super basin [41,42] and super resource basin [43,44] address integrated exploration of multiple resources, but focus exclusively on mature basins and do not explicitly address the logic of energy transition risk mitigation. To date, no conceptual framework has articulated multi-resource exploration strategies from the inception of exploratory portfolios, explicitly addressing economic resilience and vulnerability reduction under adverse demand, price, and regulatory scenarios.

Study Objectives and Contributions

To fill this scientific gap, this study proposes Co-exploration as an exploratory strategy whereby conventional O&G exploration activities and datasets are leveraged and expanded to encompass the joint assessment of alternative subsurface resources that may be developed independently or synergistically with O&G projects. Unlike common diversification strate-

gies that move away from E&P, Co-exploration proposes an integrated logic of geoscientific knowledge generation and portfolio construction, in which a common exploratory effort seeks to reduce aggregate risk, increase resilience, and decrease the risk of extreme losses associated with structural market changes.

The economic-strategic principle of Co-exploration is the creation of alternative routes for monetizing geological knowledge, reducing exclusive dependence on O&G exploratory success and the future value of hydrocarbons. Among the alternative resources considered in this analysis are geothermal energy (especially Enhanced Geothermal Systems, EGS), natural hydrogen, lithium in brines, submarine mining, geological storage, and other opportunities associated with underground reservoirs and geological formations with economic potential.

This study makes two primary contributions. First, it provides a theoretical–conceptual framework that repositions Exploration centrally within energy transition strategies. Second, it delivers a practical compatibility matrix for comparative assessment of alternative resources:

1. Theoretical–conceptual contribution: Proposes Co-exploration as a strategic framework that repositions Exploration at the center (rather than in the rearguard) of an energy transition response strategy, valuing and expanding (instead of abandoning) upstream competencies.
2. Methodological–practical contribution: Develops and presents a compatibility matrix as a comparative assessment tool for alternative resources, considering criteria of technical–operational synergy, technological maturity, strategic suitability, and environmental and climate aspects. The matrix offers O&G companies and producing countries an instrument for prioritization and selection of diversification pathways aligned with their specific competencies and contexts.

2. Risks and Uncertainties in O&G Exploration: Energy Transition Context

Oil and gas Exploration has traditionally operated under a risk framework dominated by geological uncertainties, price volatility, and project execution challenges [2]. However, the global energy transition introduces new layers of complexity and systemic risk that extend beyond traditional technical and market factors. This section synthesizes the main risks and uncertainties currently conditioning exploratory decisions and analyzes the limitations of response strategies adopted by O&G companies.

2.1. Systemic Risks of Energy Transition

The literature identifies at least five main categories of risks associated with energy transition that directly affect the economic viability of exploratory projects: (i) market risks; (ii) regulatory and political risks; (iii) technological disruption risks; (iv) financial and investment risks; and (v) reputational and social license risks. Although presented separately, these risks are interconnected and mutually reinforcing, amplifying the complexity of risk assessment processes [45].

Market risks refer to uncertainties regarding peak oil demand and price volatility, which challenge the viability of projects with life cycles spanning decades. Although oil demand has historically shown continuous growth [46], long-term prospects have become highly uncertain due to climate policies, transportation electrification, and changes in consumption patterns. IEA projections suggest that the demand peak may occur by 2030 [15], while OPEC scenarios point to continued growth until mid-century. This dispersion of projections (Figure 1) expands the decision-making uncertainty space. Moreover, the risk of

stranded assets, when assets become economically unviable before the end of their useful life, discourages long-term investments, especially in frontier areas [47–50].

Regulatory and political risks emerge from increasingly restrictive climate policies. Carbon pricing mechanisms (taxes and emissions trading systems, ETSs) are proliferating globally, increasing operational costs and threatening the economics of marginal or carbon-intensive projects [51]. Additionally, exploration moratoria, license restrictions, elimination of subsidies, and fossil fuel phase-out policies can prevent access to new reserves and render planned projects unviable [52–54].

Technological disruption risks stem from the accelerated advancement of renewable energy, fleet electrification, electric vehicles, and energy efficiency gains, which have the potential to structurally reduce oil demand and lead to a prolonged period of low prices [55,56]. This dynamic may compromise the value of hydrocarbon discoveries, reduce the attractiveness of new investments, and accelerate the obsolescence of upstream assets [15,57–59]. Moreover, the development and adoption of energy transition technologies tend to accelerate as escalating geopolitical tensions and consequent oil price volatility expose vulnerabilities of consuming countries, which, in turn, seek to reduce fossil fuel dependence, ensure energy security, and avoid inflationary shocks [60]. International relations are thus profoundly influenced by energy resource distribution and associated technologies, meaning that significant energy technology transitions imply geopolitical shifts [61]. Growing competition for technological leadership in renewable energy sectors further amplifies uncertainties regarding transition pace [62–64]. For O&G companies, especially those with significant exposure to long-cycle exploration projects, this context calls for strategic reconfiguration.

Financial and investment risks are associated with the concept of unburnable carbon, as the potential emissions from global fossil fuel reserves far exceed the carbon budget compatible with climate targets [65,66]. This implies that a significant portion of reserves would have no realizable value in accelerated transition scenarios, raising the risk of accounting impairments and a carbon bubble [47,67]. Evidence indicates that, following the Paris Agreement, financial institutions began pricing these risks into sector lending, charging higher spreads and offering shorter terms [68], which increases the cost of capital and restricts access to financing.

Reputational and social license risks arise from increasing scrutiny by investors, regulators, and civil society. The rise in climate litigation, activist shareholder pressure, and public opposition to new exploration projects can compromise permitting, lead to delays and cancellations, and generate significant financial and operational costs [69–71]. Additionally, O&G companies face difficulties attracting new professionals, especially geoscientists, due to the perception that the sector is not aligned with the energy future [39,72–74].

2.2. Company Strategies: Limitations and Gaps

Faced with this expanded spectrum of risks, O&G companies have adopted diversification strategies that vary in degree of structural transformation. Historically, diversification has always been a central tool to mitigate risks and restore profitability in the face of economic shocks and structural changes [27]. However, current responses present significant limitations.

Incremental strategies focus on optimizing internal processes, such as reduction in operational emissions (Scopes 1 and 2), electrification, flaring elimination, methane leak control, and adoption of carbon capture and storage (CCS) technologies in line with the announced pledges of the net-zero emissions target [1,75]. Although important, these measures cover less than 20% of total O&G chain emissions, while the majority occurs in final combustion by consumers (Scope 3), and require high investments without necessarily ensuring resilience against declining demand scenarios [26,38].

Portfolio reconfiguration strategies prioritize assets with rapid returns, short cycles, lower breakeven costs, and lower carbon intensity, while adopting greater financial discipline focused on shareholder returns [28–30,76]. This approach, however, limits investments in exploratory frontiers and keeps E&P spending below historical standards [37,77], compromising organic reserve replacement and increasing dependence on mergers and acquisitions (M&A) [78,79].

Radical diversification strategies involve profound structural transformations and massive investments in renewable energy (wind, solar), biofuels, green hydrogen, and other low-carbon technologies, with repositioning as "energy companies" [27,30,31,76]. European majors (Shell, BP, TotalEnergies, Eni) aggressively adopted this strategy between 2015 and 2022, with rebranding and announcements of ending exploratory expansion in new areas [35,80,81]. However, these strategies move away from the technical–organizational core of E&P, require the creation of new value chains and risk–return profiles that do not align with consolidated Exploration competencies [33]. Significantly, from 2022 onward, a retreat from these strategies has been observed, with revisions of climate targets and resumption of O&G investments by European majors, evidencing that premature abandonment of core business may be counterproductive [82–84].

Table 1 synthesizes the identified risks, their impacts on exploratory decision-making, and strategic movements adopted by companies.

Table 1. Synthesis of risks, uncertainties, and strategic movements of O&G companies.

Risk Type	Threats and Uncertainties Impacting Exploration Decision-Making	Company Strategic Movements
1. Market Risks	Uncertainties regarding peak demand and price volatility challenge the viability of projects with decades-long life cycles. The threat of stranded assets discourages long-term investments.	Portfolio review focusing on rapid-return and short-cycle assets; reassessment of strategies in frontier areas or areas without infrastructure.
2. Regulatory and Political Risks	Carbon pricing mechanisms (taxes and ETSs) and subsidy elimination threaten operational margins and the economics of marginal or carbon-intensive projects. Moratoria and license restrictions can prevent access to new reserves.	Pursuit of energy efficiency, emissions reduction in E&P (Scopes 1 and 2), and adoption of CCS (Carbon Capture and Storage) technologies.
3. Technological Disruption Risks	Advances in renewables, biofuels, electrification, EVs, and energy efficiency have the potential to reduce oil demand and lead to a prolonged period of low prices and accelerated obsolescence of upstream assets.	Diversification beyond core business, investments in renewables, H2 and biofuels; repositioning as energy companies.
4. Financial and Investment Risks	The possibility of a carbon bubble and devaluation of reserves (unburnable carbon) increases the cost of capital and restricts access to bank financing.	Greater financial discipline, prioritization of shareholder returns, and debt reduction at the expense of exploratory cost expansion.
5. Reputational and Social License Risks	The increase in climate litigation, activist shareholder pressure, and difficulty attracting talent (geoscientists). Resistance to social acceptance can delay or cancel projects.	Greater transparency of decarbonization targets (Net Zero) and climate governance; adoption of brands and names seeking identification with sustainability.

Note: ETS = Emissions Trading System; CCS = Carbon Capture and Storage; EVs = Electric Vehicles; H_2 = Hydrogen.

2.3. The Need for an Alternative Strategy

The oscillations in company strategies, ranging from optimism about renewables to recent retreats, evidence the challenge of balancing: (i) reserve replacement and cash generation in the short and medium term; (ii) operational competitiveness; and (iii) mitigation of long-term vulnerabilities in a transforming energy system [37,85].

The resilience of the upstream sector will depend not only on adaptation to carbon constraints, but also on a reassessment of the role of Exploration itself. Rather than abandoning subsurface investigation, a movement that has proven premature [84,86] and may compromise the replacement of still-needed reserves [37,38], this study proposes expanding the scope of Exploration through a strategic shift toward Co-exploration of alternatives. This approach consists of integrated pursuit of resources beyond hydrocarbons, leveraging geoscientific competencies, data infrastructure, and consolidated technical workflows to diversify exploratory portfolios without abandoning the technical–organizational core of E&P. The next section presents and characterizes this strategy in depth.

3. Co-Exploration and Alternative Subsurface Resources

3.1. Definition and Rationale for Co-Exploration

The significant reduction in upstream spending and, particularly, in Exploration investments over the past decade, resulting in levels well below historical standards and a continuing decline in the number of wildcat wells [77], reflects several factors: lower risk appetite, increased shareholder returns, focus on capital discipline (mainly by International Oil Companies, IOCs), structural sector changes, and a trend of low oil prices [37,87]. In this scenario, the relevance of Exploration in the strategy of various O&G companies appears to be diminishing, evidenced by reductions in exploration teams and the growing reliance on mergers and acquisitions (M&A) rather than organic reserve replacement [35,78,79].

Precursor concepts: super basin and super resource basin

An alternative strategy, proposed by the AAPG (American Association of Petroleum Geologists), advocates a more prominent upstream role to revitalize the O&G industry, leveraging transformative technologies developed or improved between 2000 and 2015: horizontal drilling, hydraulic fracturing, advanced seismic imaging, and petroleum systems knowledge [41,42]. This approach introduces the concepts of *super basin*, mature basins with large recoverable volumes, multiple petroleum systems, data abundance, and established infrastructure, and *super basin thinking*, treatment of sedimentary basins as integrated economic ecosystems, focusing on revisiting plays, revitalizing mature basins, and promoting economies of scale [41,88].

In the energy transition context, this concept evolved into a *super resource basin* or *energy super basin*, which seeks to transform provinces previously focused exclusively on hydrocarbons into low-carbon energy hubs, repositioning the role of geosciences beyond fossil fuels [89,90]. Considering favorable geology, existing infrastructure, and vast data legacy, super-basins are treated as multifunctional sedimentary systems in which hydrocarbon extraction enables transition to a sustainable and diversified energy system [89].

However, the strategy centered on super-basins is limited to a restricted group of mature basins and tends to focus on leveraging and extending the use of existing assets, such as depleted fields and associated infrastructure, for development of low-carbon technologies such as wind, geothermal, and CCS [89].

Definition of Co-exploration

This work proposes an adaptation and expansion of this strategy. Without being limited to mature basins and assigning Exploration a vanguard role, it introduces the concept of

Co-exploration: a deliberate exploratory strategy in which, from initial campaign planning and conception, various resources beyond hydrocarbons are sought, aiming to capture technical and economic synergies. Although anchored in hydrocarbon exploration, the Co-exploration campaign is defined by a broader and more diversified scope: its secondary targets are subsurface-related resources and services whose prospection is closely related to geosciences and the O&G upstream sector.

Among the potential alternative resources to be co-explored, generally associated with a low-carbon economy, the following can be cited: geological storage of CO_2, methane, H_2, or thermal energy; occurrences of natural H_2 and associated elements (He); utilization of geothermal energy; and recovery of critical and strategic metals from brines or submarine deposits (crusts and nodules).

Strategic principles

The objective of the Co-exploration strategy is to promote diversification related to O&G sector capabilities and enable the construction of an options portfolio from a common base of knowledge and expertise in operations and logistics, to reduce uncertainties and increase expected value. This could be achieved through the possibility of aggregating multiple revenue streams. Unlike the super basin thinking strategy, which focuses on mature basins to optimize O&G gains (albeit integrated with low-carbon businesses), Co-exploration is proposed as an integrated exploratory diversification strategy, explicitly oriented to reduce long-term risks and expand value pathways by combining O&G with alternative resources from the same architecture of data, decisions, and projects.

The proposed Co-exploration strategy requires more than mere coexistence of opportunities; it demands integration of the decision-making process from play conception onward, including area selection criteria, multiphysics and geochemical data planning and acquisition, wildcat well design, and leveraging core business competencies and routines to evaluate and test multiple adjacent value chains. This represents, therefore, an adjacent diversification and growth strategy that leverages existing assets and capabilities to expand operational boundaries [91,92]. At the same time, it protects and strengthens current operations while expanding frontiers and testing new opportunities supported by capabilities that have already been mastered, thereby reducing implementation risks [93].

The implementation of Co-exploration, being a comprehensive adaptation strategy, should involve changes in investments, operations, R&D and, ideally, a coalition between E&P companies and regulatory agencies [33].

Strategic value

The Co-exploration strategy has the potential to redefine the geoscientist's role as an integrator of low-carbon solutions and recover the relevance of the upstream segment, especially Exploration, considering energy transition advances [39,40]. Maintaining Exploration relevance is fundamental because, even under accelerated energy transition, traditional O&G exploratory activity will remain necessary in the short and medium term, given energy security imperatives, natural field decline, geopolitical volatility, and pressure for selective replacement of low-cost, low-risk reserves [38].

For O&G companies, Co-exploration seeks to ensure economic resilience and geopolitical relevance. The strategy allows diversification and integration of the portfolio, with resources that could increase asset sustainability under stricter regulations and offer opportunities for business-model extension [33].

For producing countries whose economies depend on oil revenues, Co-exploration can promote economic diversification and energy sovereignty [94]. The strategy favors using O&G revenues to finance new sectors and value chains (critical minerals, renewable energies) [95,96]. Potential substitution of domestic hydrocarbon consumption by

renewable sources can free larger volumes for export, increasing revenues in the short term. Meanwhile, fossil fuel production integrated with low-carbon solutions, leveraging assets and sharing infrastructure, can decrease emission intensity, extend asset life, and reduce stranded asset and carbon bubble risks [97].

Pioneer example: Ordos Basin (China)

It is worth mentioning the Ordos Basin in China as a practical and pioneering example of a hybrid development model of integrated multi-resource exploration that bears similarities to the proposed Co-exploration strategy, although with a scope still limited to mature basins [43,44,98,99]. Characterized as a super resource basin or energy super basin, the vast intracratonic sedimentary Ordos Basin hosts systems where conventional and unconventional hydrocarbons coexist with strategic mineral deposits (sandstone-type uranium, lithium and germanium in coal), allowing infrastructure and geoscientific knowledge from the O&G industry to be transferred for coordinated extraction of these resources [43,99]. Additionally, there is integration of renewable energy production on the surface (high solar and wind potential), use of the subsurface for geothermal energy recovery, and CO_2 storage from local industries in depleted reservoirs and saline aquifers [99].

Driven by China's National Energy Administration (NEA) "Action Plan to Accelerate the Integrated Development of Oil and Gas Exploration and New Energies (2023–2025)," the approach aims to transform the Ordos Basin into a low-carbon energy hub with synergistic exploration of multiple resources [98,100,101].

The exploratory approaches discussed are synthesized in Table 2, illustrating the evolution of exploration concepts from strategies focused on individual hydrocarbon plays to integrated approaches targeting multiple subsurface resources. The comparison highlights how the Co-exploration strategy distinguishes itself by explicitly prioritizing portfolio diversification and the integration of alternative resources from the outset of the exploratory project, thereby addressing the risk and uncertainties associated with the energy transition.

Table 2. Synthesis of exploratory concepts.

Concept	Super Basin (AAPG)	Super Resource Basin	Co-Exploration
Scope	Mature basins	Mature basins	All basins + frontiers
Timing	Revisit/retrofit	Subsequent coexistence	Integration from conception
Focus	Maximize O&G	Low-carbon hub	Diversification + resilience
Exploration Role	Final optimization	Coordinated transition	Strategic vanguard
Decision	Isolated by resource	Isolated by resource	Integrated multi-resource

3.2. Alternative Resources Integrable with Oil and Gas Exploration

This section presents five categories of alternative subsurface resources that can be identified, characterized, and developed jointly with traditional O&G exploration. The analysis consolidates the essential characteristics of each resource, demonstrating how technical–operational synergies, accumulated geological data, existing infrastructure, and O&G industry competencies can be leveraged to mitigate risks and create new value sources in an energy transition context.

3.2.1. Geothermal Energy: Expanding the Geographic Base of Thermal Energy

Geothermal energy corresponds to the utilization of heat from Earth's interior, originating from residual heat from the planetary accretion process and continuous decay of natural radioactive isotopes [102]. The temperature differential between surface and core

promotes a continuous thermal energy flow of approximately 45 terawatts to the surface, driving tectonic dynamics in Earth's crust. Geothermal systems exploit the thermal gradient in the crust, whose temperature increases on average 25–30 °C per kilometer of depth, for direct use in heating and cooling, electricity generation, or energy storage [103].

Conventional geothermal systems, dependent on naturally present hydrothermal fluids and permeable rocks, concentrate geographically in regions with higher geothermal gradients, generally associated with plate boundaries, active volcanic regions, or crustal extension areas. Despite being a mature technology used for over a century, conventional geothermal remains geographically restricted and its global potential largely unexplored [104]. For depths below 5000 m, global technical potential is on the order of 42 TW of capacity over 20 years; between 5000 and 8000 m, this potential exceeds 550 TW, reflecting the wide availability of high-temperature resources across much of the globe [105].

Recent approaches seek to overcome geographic restrictions through technologies that do not depend on hydrothermal resources or natural rock permeability. Enhanced Geothermal Systems (EGSs) enable thermal energy recovery from low-permeability geological formations through fracture creation or intensification by hydraulic, thermal, or chemical stimulation [106,107]. Developed since the 1970s as Hot Dry Rock (HDR) System, EGS involves drilling wells to zones of interest, typically crystalline rocks at 4–5 km depth, followed by stimulation to increase permeability and fracture connectivity, enabling working fluid circulation (usually water) between injection and production wells [108]. Heated fluid returns to the surface for direct thermal use or electricity conversion via a steam turbine or Organic Rankine Cycle (ORC) at low temperatures [109,110]. EGS technologies are in an advanced pilot phase, with the first commercial projects already under execution, delivering significant performance improvements and reductions in drilling time and costs through the successful adaptation of oil and gas techniques [111].

Advanced Geothermal Systems (AGSs), or Closed-Loop Geothermal Systems (CLGSs), use sealed wells and a working fluid that circulates without direct contact with rock, transferring heat by conduction through wellbore walls. Although AGS present lower heat transfer efficiency, they minimize risks of aquifer contamination, fluid losses, and induced seismicity. A promising variant is the CO_2-Plume Geothermal (CPG) system, which uses supercritical CO_2 as working fluid injected into a permeable reservoir underlying a sealing layer. Once heated, part of the CO_2 returns to the surface, providing thermal energy and, after cycling, is reinjected, being permanently stored—integrating geothermal generation with carbon sequestration [112].

Geothermal energy presents the highest technical–operational overlap with O&G upstream. Competencies in deep-well drilling, reservoir characterization under high-pressure, high-temperature (HPHT) conditions, seismic data interpretation, fluid flow modeling in porous media, reservoir stimulation via hydraulic fracturing, and complex project management are directly transferable [113]. Sedimentary basins already mapped for petroleum can be repurposed for identifying potential geothermal reservoirs, reducing marginal costs and exploratory uncertainties [114]. Recent adaptation of O&G industry strategies for EGS well drilling has promoted significant time and cost reductions, while infrastructure sharing and logistical integration have the potential to reduce technical and financial risks [106,115]. Mature or abandoned O&G wells can be converted for geothermal utilization, postponing decommissioning, while offshore platforms and pipelines can be adapted for thermal fluid transport [103,116,117]. Geothermal energy cogeneration can contribute to increased energy efficiency and reduced emissions associated with O&G production, while revenue stream diversification can attenuate exposure to oil price fluctuations and potentially reduce stranded asset risk [118,119].

EGS can also be applied to lithium extraction associated with hypersaline fluids from stimulated geothermal sources [120]. In western Germany, pilot plants in the Upper Rhine Valley produce between 1000 and 1500 tons/y of lithium carbonate equivalent [121,122]. Over the past decade, the emergence of companies and startups seeking to exploit geothermal potential through innovative techniques has been observed, with investments from energy-intensive sectors and O&G companies. Traditional service providers such as SLB, Baker Hughes, and Halliburton already offer specific drilling, stimulation, and monitoring solutions for unconventional geothermal projects [103,105]. Despite advantages over conventional systems, EGS still faces technical and economic challenges before achieving commercial scale, including induced seismicity control, ensuring aquifer non-contamination, water resource management, maintaining long-term productivity, material durability in HPHT conditions, and high drilling and stimulation costs at great depths [123,124].

3.2.2. Lithium in Brines: Transforming Produced Waters into Strategic Resource

Geological brines are hypersaline waters circulating or accumulating in Earth's crust, frequently enriched in divalent cations, sulfates, and trace metals. Growing lithium demand, which more than doubled between 2021 and 2024 due to lithium-ion battery production for electric vehicles and stationary storage systems, drives interest in alternative extraction sources [125]. Although spodumene deposits in hard rocks dominate current global production, lithium-enriched brines represent approximately 75% of globally identified reserves, concentrated in the Central Andes zone (Argentina, Bolivia, Chile), where traditional exploitation depends on solar evaporation in salars, a slow process (12–24 months) with high water consumption and significant environmental impacts [126].

Emerging technologies such as Direct Lithium Extraction (DLE), based on selective adsorption, ion-exchange, or membrane separation processes, enable the rapid and continuous recovery of lithium from brines, eliminating the need for solar evaporation and improving the economic viability of resources previously considered marginal [127]. In this context, three geological settings stand out as having significant potential for integration with the oil and gas (O&G) industry: deep saline aquifers in sedimentary basins; brines associated with geothermal systems; and produced waters from O&G fields, previously treated as an environmental liability [128,129].

Produced waters from oilfields constitute a particularly relevant opportunity for the O&G industry. Such interest stems from the large volume and continuous flow of already co-produced brines, which represent significant exploitable potential [128]. In Brazil, lithium occurrences in produced waters have been recorded in offshore fields in the Northeast and Southeast regions, with concentrations between 60 and 200 mg/L and values above 300 mg/L in pre-salt fields of Santos Basin [130–133]. In the Salton Sea (California), with historical records up to 983 mg/L, plans exist for the first commercial-scale plant using DLE in the USA [134]. Annual brine production associated with geothermal energy generation in the region is estimated to potentially generate up to 127 thousand tons of lithium carbonate equivalent per year, with total potential resource up to 18 million tons [135].

Lithium brine exploration in sedimentary basins can directly benefit from O&G industry experience in using geophysical prospection methods, petrophysical and geochemical analyses, and reservoir characterization, fundamental for adequate brine recovery and reinjection. Utilization of data such as well logs, cores, and geochemical analyses of produced waters, combined with the possibility of sharing production and fluid treatment infrastructure, constitutes a competitive advantage with consequent cost and development timeline reduction [127]. Co-production with lithium recovery units integrated into O&G production operations can transform the waste stream into a strategic resource. From a circular economy perspective, brines offer potential for simultaneous extraction of other minerals of

economic interest such as borates, magnesium, potassium, and sodium salts [136]. This synergy can be further expanded through technological and strategic integration with carbon capture and storage (CCS) projects, since deep saline systems constitute potential geological CO_2 reservoirs and, if lithium-enriched, targets for critical metal extraction [136,137].

Regulatory frameworks such as the Inflation Reduction Act (IRA) in the USA and the European Union's Critical Raw Materials Regulation, which promote domestic critical mineral production through tax credits for extraction and processing, favor project financial viability [138,139]. However, expansion depends on scale validation and DLE technology maturation, overcoming challenges in managing brine chemical complexity, and strategic incentives capable of reducing dependence on China-dominated supply chains through subsidies, tax credits, and price stabilization mechanisms to mitigate market volatility [125,138,140]. Although considered more environmentally sustainable than traditional mining, lithium extraction from brines presents relevant limitations, including significant freshwater consumption (critical in regions of high water stress), generation of large volumes of solid waste, induced seismicity risk associated with extraction and reinjection of large fluid volumes, presence of potentially toxic elements in brines, and high energy intensity of separation and chemical conversion processes, which may compromise lithium climate benefits if energy used is not from renewable sources [125,128,135,140].

3.2.3. Submarine Mining: Opportunities and Risks on the Seafloor

Growing demand for critical minerals for batteries, wind turbines, electric motors, and electrical distribution infrastructure, combined with concerns about geographic supply concentration and its geopolitical consequences, directs the mineral exploratory frontier to deep marine environments [125]. Submarine mining targets production of cobalt, copper, nickel, manganese, and rare earth elements in high-grade deposits located on the seafloor at depths exceeding 200 m, found in three main deposit types: polymetallic nodules, cobalt-rich crusts, and massive polymetallic sulfides [141].

Polymetallic nodules are rounded concretions formed on abyssal plains (3500–6500 m), with a concentric structure of manganese and iron oxides precipitated around nucleating fragments, presenting slow growth rates (1–8 mm/million years) under very stable environmental conditions [141,142]. Formation can occur through hydrogenetic precipitation (directly from seawater) or diagenetic (from sediment pore water), directly influencing chemical composition: hydrogenetic nodules (Mn/Fe < 4) are richer in cobalt and rare earth elements, while diagenetic (Mn/Fe 5 to 800) are enriched in nickel and copper [143]. The Clarion–Clipperton Zone (CCZ, North Equatorial Pacific) is the largest and most promising area, with estimates exceeding 500 million tons of dry nodules and significant grades of Mn, Ni, Cu, Co, Mo, and REE, containing 19 of 31 contracts granted by the International Seabed Authority (ISA) [144,145]. Other relevant occurrences include Cook Islands Exclusive Economic Zone (58 kg/m^2, high Co 0.41%, Ni 0.38%, REE+Y 0.167% grades) [146,147], Central Indian Ocean Basin (~380 Mt) [148], and Peru Basin [149,150].

The offshore O&G industry presents relevant technical–operational synergies for submarine mining, including seismic exploration and remote sensing technologies, deepwater and ultra-deepwater operations, ROVs and subsea systems, experience in offshore logistics and environmental management of marine operations, and the possibility of repurposing decommissioned offshore production infrastructure. Operational integration can reduce costs and risks by promoting a coordinated approach for exploration of diverse resources in deep marine environments. Beyond economic aspects, interest in submarine mining has strategic and geopolitical dimensions, whether through the importance of commanding critical mineral supply chains for technologies essential to energy transition, defense, and electronics [61,62,94], or as a form of maritime sovereignty reinforcement, with mapping

and exploration in exclusive economic zones potentially subsidizing territorial expansion claims [151–154].

Despite the strategic potential of marine mineral deposits, which frequently present grades and volumes superior to known terrestrial reserves [155], significant associated environmental risks exist. Studies observe that biodiversity in deep areas is still poorly known and mining activity would inevitably disturb seafloor habitat [156–158]. Nodule and crust removal may destroy ecosystems formed over thousands of years, while during extraction, ore elevation, and tailings treatment there is potential for sediment dispersion and release of heavy metals and toxic substances that can contaminate the water column, cause damage to filter-feeding species, and affect food chains [149,159]. Noise and vibrations can impact sensitive marine species such as cetaceans and deep-water fauna [158]. Undefined international standards, scientific uncertainties about actual impacts, negative public perception, and non-governmental organization pressure can generate reputational costs to companies and governments advancing pioneer projects [160–163]. Very high operational costs, absence of commercial projects for benchmarking, and still-incipient technological maturity constitute additional economic barriers [164].

3.2.4. Natural Hydrogen and Helium: Subsurface Gases with Strategic Potential

Natural Hydrogen

Natural hydrogen, also termed geological, native, or "white" hydrogen, consists of H_2 gas found naturally in its molecular form in the subsurface. Although occurrences have been known for over a century, they were historically treated as a mineralogical curiosity or contaminant in O&G reservoirs. In the energy transition context, low-carbon hydrogen is considered a bet for decarbonizing hard-to-abate industrial sectors and transportation [165]. The IEA considers hydrogen an important energy vector in all its scenarios to 2050, especially in Announced Pledges and Net-Zero Emissions by 2050 scenarios [166]. However, projections are restricted to synthetic hydrogen obtained primarily by electrolysis, dependent on primary energy sources. Due to this dependence, hydrogen's role in the energy transition is controversial [167,168].

Over the past decade, growing scientific and economic interest in natural H_2 occurrences has been observed, including their understanding and search for potential flows or reserves that can be exploited as a carbon-free energy source [169,170]. Previously considered rare, the possibility of significant natural hydrogen accumulations was reassessed in the last 10 years, driving interest in geological-origin gas due to its potential as a renewable energy source whose combustion is free of CO_2 emissions. Continuously produced inside the Earth, natural hydrogen is commonly observed in diffusive surface exhalations and subsurface interceptions by mineral drilling or hydrocarbon wells. Being a colorless, odorless, and non-toxic gas, although highly flammable, its detection and verification are difficult and, as specific analyses are not common, occurrences tend to be ignored [171]. There is a reasonable set of observations, with H_2 contents exceeding 10%, pointing to occurrences in a wide variety of geological environments and broad geographic distribution, suggesting a diversity of generation mechanisms [172]. Hydrogen analyses are not routinely performed in wells and boreholes; therefore, occurrences are often identified by chance ("serendipity"), belatedly, tending to be underestimated. In the Khibiny Massif (Russia), despite recent studies revealing H_2-rich gases present in all studied mines, the first occurrence was only discovered after more than 20 years of research work in the region [173].

Serpentinization processes (reaction of ultramafic rocks with water in the presence of Fe^{2+}) and deep degassing are considered the main mechanisms in terms of volumes generated, with radiolysis and iron reduction/sulfur oxidation processes contributing significantly in smaller proportions. Relevant occurrences include Mount Chimera (Turkey,

"eternal fires" since antiquity, 17–22 t/year of H_2), Philippines (44% concentration), Mali (98% purity, 1500 m^3/day, the only case of commercial production to date) [172,174,175]. Recent studies detected emanations in cratonic regions in South Africa, Australia, Brazil, USA, Finland, and Russia, frequently associated with "fairy circles" recognizable by satellite. In the São Francisco Craton (Bahia, Brazil), emissions were recorded with flows between 7000 and 178,000 m^3/day [176]. In Bulqizë (Albania), release at high concentrations (up to 84%) was identified in a chromite mine, with estimated flows of 11 t/year in the fault zone and total potential between 5000 and 50,000 tons [177].

Natural hydrogen exploration presents synergies with O&G through adaptation of petroleum systems models (generation, migration, accumulation, seal), regional seismic, geochemical, gravimetric, and well data supporting assessment of generating and accumulating systems, drilling and well-testing capacity, knowledge of gas migration and seals, and possibility of co-production with hydrocarbons [178]. Considering modest expectations and smaller accumulations, natural hydrogen may play an important role when used for local electricity generation through combustion or fuel cells (more efficient solution). As H_2 production could be controlled, such electricity generation could be integrated with intermittent sources (solar and wind) for a stable and predictable energy supply, complementing other hydrogen production forms (green, blue), diversifying the energy mix and, due to low cost, helping develop necessary infrastructure for the hydrogen chain. Beyond energy purposes, it could be used in ammonia and fertilizer production with lower emissions. Throughout the evolution of human civilization's energy systems, the succession of dominant fuels, from firewood to coal, then oil and natural gas, inadvertently followed a trajectory toward a lower carbon-to-hydrogen ratio [179,180]. In this context, hydrogen can be understood as the limit of this trend and, considering similarities with hydrocarbon occurrences and prospections, a potential alternative resource to be explored by O&G companies.

Challenges include uncertainty about economically recoverable volumes, lack of consolidated models for H_2 generation and accumulation systems, low energy density (requires large volumes), need for storage and transport infrastructure, safety risks (flammability), very low technological maturity, only one small-scale commercial project worldwide, nonexistent market, and potential competition with green/blue H_2.

Helium

A noble gas essential for medical applications (magnetic resonance imaging), scientific (cryogenics), aerospace, and industrial uses, helium is a non-renewable resource on human timescales, generated by radioactive decay of uranium and thorium in crustal rocks, with accumulations in reservoirs associated with nitrogen-rich natural gas. Helium exploration and production demonstrates significant synergies with the O&G sector, as the primary helium provinces geographically coincide with petroleum-producing regions, enabling the application of analogous exploration workflows, the use of similar structures and seals for entrapment, and the leveraging of existing infrastructure, with helium being historically discovered as a by-product of natural gas in O&G operations [181]. It faces challenges such as very low concentrations in most reservoirs (<0.3 mol%), high separation and purification costs, a restricted and geographically concentrated market (USA, Qatar, Algeria), price volatility, and risk of strategic reserve depletion [182,183].

3.2.5. Geological Storage: Carbon Capture and Storage as Natural Upstream Extension

Geological storage consists of fluid injection into deep subsurface rock formations for permanent isolation or temporary storage [184]. Practices established for decades include natural gas storage in depleted reservoirs and salt caverns to balance seasonal

supply/demand fluctuations, and disposal of industrial liquid wastes and produced waters in saline formations [185]. Emerging possibilities include underground compressed air and hydrogen storage, converting surplus renewable-generated electricity into potential or chemical energy, acting as batteries of different scales for intermittency reduction and promoting greater energy security [186,187].

Among substances storable in the subsurface, carbon dioxide (CO_2) attracts the greatest interest, concentrating most research efforts and resources. This stems from CO_2 being the main anthropogenic greenhouse gas (GHG); therefore, its permanent confinement is an important tool in carbon management to mitigate climate change. Additionally, CO_2 injection into O&G reservoirs has been a common practice since the 1970s to increase the recovery factor. Carbon Capture and Storage (CCS) technology aims to reduce carbon dioxide emissions from various industrial processes, especially in hard-to-abate sectors such as heavy industry and energy generation, fundamentally consisting of three stages: capture (CO_2 separation from residual gases emitted by industrial processes or fossil fuel combustion), transport (compression and transport via pipelines or ships) [185,188], and storage (supercritical CO_2 injection into geological formations at depths exceeding 800 m) [189,190].

As an alternative to capture of residual gases from fixed sources, Direct Air Capture (DAC) technology extracts CO_2 directly from the atmosphere using chemical sorbents or physical processes [191]. When combined with geological storage, DAC offers a pathway for net negative emissions. Significant advantages include the possibility of positioning directly at the storage or use site, eliminating the need for complex transport infrastructure, and the stability of atmospheric CO_2 concentration over time [192]. Conversely, it faces significant limitations such as intense energy demand associated with the inefficient capture process (extremely low atmospheric concentration and negative Gibbs free energy of formation) and high operational and capital costs, hindering large-scale implementation [193].

Storage types include deep saline aquifers (greatest global storage potential), depleted O&G reservoirs (utilization of mature fields with detailed characterization and existing infrastructure), Enhanced Oil Recovery (EOR) with CO_2 (injection for additional oil recovery with partial storage), and basaltic formations (permanent CO_2 mineralization). CCS technology is applicable in various sectors: fossil-based baseload electricity generation, industrial processes in hard-to-abate sectors (cement, steel, petrochemicals where emissions are inherent to processes) [194], low-carbon hydrogen production, and association with bioenergy (BECCS), enabling negative emissions by combining renewable biomass energy with non-fossil CO_2 capture.

The sector with the deepest relationship with CCS technology is the O&G industry, which has developed over more than a century advanced tools and methods—seismic surveys, drilling technologies, petrophysical logs, and reservoir modeling—directly transferable to CCS [195]. Given accumulated geoscientific data, potential infrastructure sharing, and urgent need for energy sector decarbonization, the O&G segment has become the largest driver of CCS projects worldwide [196]. Synergies are the highest among all alternative resources, including competencies in reservoir and seal rock characterization, flow modeling in porous media, injection well drilling and completion capacity, transport infrastructure (pipelines) and monitoring (4D seismic), and repurposing of depleted assets.

Challenges include high costs of capture, transport, and injection; need for robust regulatory framework (long-term liability, pore space ownership); social acceptance (perception of leakage risk, induced seismicity); economic viability strongly dependent on carbon pricing (taxes, credit markets); competition for pore space with other alternatives (hydrogen, compressed air); and significant project delays and cancellations (more than 206 projects with delays and over 100 cancelled between 2005–2024) [197–199].

Therefore, this section demonstrated the diversity of strategic integration opportunities with O&G Exploration, each resource presenting a distinct profile of synergies, technological maturity, challenges, and potential contribution to exploratory portfolio resilience in the energy transition context, supporting the construction of the Compatibility Matrix presented in the following section.

4. Compatibility Matrix: Strategic Assessment Tool

4.1. Methodology for Compatibility Matrix Development

Diversifying the exploratory portfolio through Co-exploration requires clear criteria to identify which alternative resources best align with the strategy, considering not only technical–operational aspects but also strategic, market, environmental, and regulatory factors. This study employs a compatibility matrix developed through a structured qualitative assessment framework designed to evaluate, through Multi-Criteria Analysis (MCA), the strategic suitability of alternative subsurface resources for integration with O&G exploration activities under the Co-exploration concept.

The compatibility matrix deliberately encompasses diverse resource categories, including resource-based assets (geothermal energy, lithium in brines, natural hydrogen, helium), technological/infrastructure solutions (CCS, CO_2-EOR, H_2 storage), and a distinct industrial sector (deep-sea mining), to reflect the actual strategic landscape faced by O&G companies exploring diversification pathways in the energy transition context. It does not compare resources with technological solutions or a new mining sector. It compares the activities related to them and how they can be co-undertaken with hydrocarbon exploration activities.

Indeed, while these alternatives differ fundamentally in their nature, they share a common strategic dimension: they all represent potential applications of accumulated geoscientific competencies, legacy data, and existing upstream infrastructure beyond conventional hydrocarbon production. The Co-exploration framework is not limited to the development of new energy or mineral resources per se, but encompasses any subsurface-related activity that can leverage O&G exploration capabilities to potentially create value and reduce portfolio risk. Therefore, this inclusive approach enables a comprehensive strategic comparison that would not be possible if resources were assessed in isolation within their respective categories.

Assessment Criteria

The proposed compatibility matrix uses eleven assessment criteria identified through an extensive literature review of energy transition strategies, resource diversification frameworks, and petroleum industry best practices. These criteria were specifically designed to be applicable across all categories, capturing both technical synergies and broader strategic considerations (market dynamics, regulatory environment, ESG alignment). This allows decision-makers to compare the relative attractiveness of fundamentally different options on a common analytical basis, which is precisely the challenge faced in real-world portfolio construction. All eleven evaluation criteria are described as follows:

1. *Geological Synergy (O&G Exploration)*: Degree of overlap between geological concepts, formation processes, geotectonic contexts, and exploratory models relevant to O&G and the alternative resource. High synergy enables direct transfer of geoscientific knowledge.
2. *Utilization of G&G Data*: Potential for direct reuse of legacy geological and geophysical data (seismic, well logs, modeling) or data to be acquired, minimizing the need for dedicated campaigns and reducing entry costs.

3. *Technical and Operational Synergy*: Compatibility between methods, technologies, and operational processes (drilling, completion, stimulation, reservoir monitoring, fluid management) between O&G and the alternative resource.
4. *Potential for Infrastructure & Logistics Sharing*: Viability of repurposing existing physical assets (platforms, pipelines, operational bases, processing systems) and logistics (transport, supplies, workforce).
5. *Technological Maturity*: Development stage of technologies necessary for exploration, development, and commercial production (TRL—Technology Readiness Level scale), determining execution risks and cost predictability.
6. *Market Expectations (maturity and demand)*: Existence, maturity, and growth projections of markets, including pricing mechanisms, supply/demand structure, and revenue predictability.
7. *Capital Intensity*: Relative volume of required investments (CAPEX) and operational costs (OPEX). Note: Inverted scale; the lower the capital intensity, the higher the score.
8. *Risk Reduction Potential*: Capacity of the alternative resource to act as a hedge against energy transition risks (O&G price volatility, regulatory changes, climate constraints), diversifying value sources.
9. *Strategic Alignment*: Suitability of the alternative resource to long-term corporate objectives (decarbonization, energy transition, portfolio diversification, maintenance of operational and geopolitical relevance).
10. *Political and Regulatory Support*: Existence of favorable regulatory frameworks, incentive policies (tax credits, subsidies, carbon pricing), government programs, and institutional acceptance.
11. *Environmental, Climate, and Social Suitability*: Contribution to climate objectives (emissions reduction, alignment with Net Zero), relatively controlled environmental impacts, and social acceptance (social license to operate).

These criteria encompass four main dimensions:

(I) Technical–operational synergies (geological synergy, G&G data utilization, technical and operational synergy, infrastructure sharing potential);
(II) Economic and market factors (technological maturity, market expectations, capital intensity);
(III) Strategic alignment (risk reduction potential, strategic fit, political and regulatory support);
(IV) Sustainability considerations (environmental, climate, and social suitability).

These dimensions capture the multifaceted nature of strategic resource integration, reflecting not only immediate technical feasibility but also long-term viability, market dynamics, the regulatory environment, and alignment with decarbonization objectives.

Rating Scale and Scoring Process

To enable multi-criteria evaluation of the alternatives, a five-point Likert-type scale (1, very low, to 5, very high) was adopted to allow nuanced differentiation among alternatives while maintaining analytical tractability. Each criterion was evaluated based on published technical literature and case studies; industry reports and project databases; regulatory frameworks and policy documents; and expert knowledge from petroleum geosciences and energy transition domains.

Evidence from multiple sources documented in the main text and the Supplementary Material SI (SM SI) was synthesized to assign scores to each alternative resource. The SM SI provides a comprehensive description of these criteria, including rating scales and the specific aspects the authors considered when evaluating each alternative resource. Additional references [200–245] supporting the scoring framework are provided in the

Supplementary Materials and complement those cited in the main text. For further details, please refer to the Supplementary Materials.

The compatibility score was calculated using a weighted multi-criteria approach. First, the evaluation criteria were organized into four thematic dimensions, each comprising a set of related attributes. For each dimension d, the arithmetic mean of the corresponding criteria scores was calculated. Subsequently, a weighting factor w was assigned to each dimension to reflect its relative importance in the overall assessment. The final compatibility score was obtained by summing the weighted mean scores of all dimensions, as expressed by Equation (1):

$$S = \sum_{d=1}^{n} w_d \cdot \bar{c}_d \quad (1)$$

where S is the overall compatibility score for each resource category, n is the number of dimensions, w_i is the weight assigned to dimension d, and $\bar{c}_i$ is the mean score of the criteria belonging to that dimension. This procedure adjusts each dimension's contribution according to its relevance while preserving the influence of individual criteria within each group.

In the baseline analysis, equal weighting was applied to all criteria, reflecting the exploratory nature of this initial framework. However, employing a Multi-Criteria Analysis and assigning differential weights to each criterion or criteria dimension would provide a more context-sensitive framework, enabling the incorporation of organizational priorities, regional characteristics, and strategic objectives into the assessment process. Accordingly, an exercise of sensitivity analysis considering alternative weighting schemes was incorporated into the study, allowing the robustness of the results to be evaluated under different weighting assumptions.

4.2. Comparative Analysis of Alternative Resources

The Compatibility Matrix (Table 3) presents a qualitative assessment that synthesizes the suitability of the eight alternative resources across eleven structured evaluation criteria grouped into four dimensions. Equal weighting was assigned to all criteria and dimensions, providing a balanced comparative framework to support strategic decisions on resource prioritization and integration.

Table 3. Compatibility matrix, scale from 1 (very low) to 5 (very high).

Dimensions	I Technical–Operational Synergies				II Economic and Market Factors			III Strategic Alignment			IV Sustainability Considerations	
Alternative Resources	**Geo Syn.**	**GG Data Use**	**Tech/ Oper. Syn.**	**Infra & Logistics**	**Tech Maturity**	**Market Expec.**	**Capital Int. ***	**Risk Red.**	**Strat. Fit**	**Pol. & Reg. Support**	**ESG Suitability**	**Total Score**
Geothermal (EGS)	5	5	4	4	4	4	2	4	5	5	4	**4.125**
Lithium (brines)	4	5	4	4	4	5	4	4	4	3	4	**4.063**
CO_2-EOR	5	5	5	5	5	4	3	3	4	3	2	**3.583**
CCS	5	5	5	5	4	3	2	3	5	4	4	**4.000**
H_2 storage	4	4	3	4	4	2	3	3	4	3	5	**3.771**
Submarine mining	1	2	4	2	2	5	1	4	2	1	1	**2.063**
Natural H_2	3	3	4	1	2	2	3	5	5	3	5	**3.604**
Helium	4	3	4	3	4	4	3	3	3	3	3	**3.292**

* Inverted scale.

The matrix reveals three distinct strategic suitability profiles:

High-compatibility resources (≥4 points):

1. *Geothermal energy (EGS)* and *Lithium (brines)* emerge as the most balanced alternatives, combining strong technical–operational and geological synergies, high utilization of

G&G data, long-term strategic alignment, and environmental-climate suitability. Both offer robust diversification pathways with moderate technological risk profiles and expanding markets.

2. *CO_2 storage (CCS)* presents high technical–operational synergies and infrastructure repurposing capacity, in addition to consolidated technological maturity. However, it offers lower diversification potential (CCS depends on carbon markets still under consolidation) and faces criticism regarding long-term environmental and climate suitability, although it plays a relevant role in the transition.

Intermediate-compatibility resources (3 to 4 points):

1. *H_2 storage* presents moderate technical synergies and high environmental suitability but faces still-incipient markets and technological uncertainties related to hydrogen reactivity in the subsurface.
2. *Helium* and *natural H_2* have distinct profiles: helium presents a mature market and high-value strategic niches but limited volumes and restricted geographical opportunities; natural hydrogen, despite high strategic potential and risk reduction capacity, suffers from very low technological maturity and market uncertainty.
3. *CO_2-EOR* presents the highest technical–operational synergies, infrastructure repurposing capacity, and advanced technological readiness. Nevertheless, the strong dependence on oil prices restricts its diversification potential. In addition, EOR faces considerable criticism as it ultimately extends the productive life of hydrocarbon assets and may be perceived as reinforcing long-term reliance on fossil fuels.

Low-compatibility resource (<3 points):

1. *Submarine mining* constitutes, in this analysis, the most fragile alternative, with minimal geological synergies, poorly understood environmental impacts, absence of a consolidated regulatory framework, extremely high capital intensity, and significant social/scientific opposition. Despite growing demand for critical minerals, entry barriers remain prohibitive in the short- and medium-term horizons.

This assessment is inherently qualitative and reflects the authors' interpretation of available evidence and expert judgment. The scores should therefore be understood as indicative rankings rather than absolute measurements. The narrow margin separating the leading alternatives suggests the results are highly sensitive to criterion weighting and prioritization should remain context-dependent; therefore, a sensitivity analysis considering alternative weighting schemes is presented in the next section.

4.3. Sensitivity to Criterion Weighting

To evaluate the robustness of the results and the influence of the weighting scheme, a sensitivity analysis was performed by recalculating the compatibility scores under ten different weight combinations assigned to the dimensions (Table 4), as follows:

Table 4. Weight combinations assigned to the dimensions of the compatibility matrix considered in the sensitivity analysis, including an equal-weighting baseline as a neutral starting point.

Weighting Combinations/Scenarios \ Dimensions	I Technical–Operational Synergies	II Economic and Market Factors	III Strategic Alignment	IV Sustainability Considerations
BASE	0.25	0.25	0.25	0.25
A	**0.5**	0.3	0.1	0.1
B	**0.4**	0.2	0.2	0.2
C	0.2	**0.5**	0.2	0.1
D	0.2	**0.4**	0.3	0.1

Table 4. *Cont.*

Weighting Combinations/Scenarios \ Dimensions	I Technical–Operational Synergies	II Economic and Market Factors	III Strategic Alignment	IV Sustainability Considerations
E	0.2	0.2	**0.4**	0.2
F	0.2	0.1	**0.4**	0.3
G	0.1	0.2	**0.4**	0.3
H	0.2	0.1	**0.5**	0.2
I	0.1	0.2	**0.5**	0.2
J	0.1	0.1	**0.5**	0.3

A sensitivity analysis considering alternative weighting schemes is presented in Table 5.

Table 5. Sensitivity analysis results based on ten different weight scenarios assigned to the compatibility matrix dimensions.

Alternatives \ Weighting Scenarios	BASE	A	B	C	D	E	F	G	H	I	J
Geothermal (EGS)	4.125	4.117	4.200	3.900	4.033	4.233	4.300	4.183	4.367	4.250	4.317
Lithium	4.063	4.192	4.100	4.150	4.083	3.983	3.950	3.958	3.917	3.925	3.892
CO2-EOR	3.583	4.233	3.867	3.867	3.800	3.533	3.333	3.233	3.467	3.367	3.167
CCS	4.000	4.200	4.200	3.700	3.800	4.000	4.100	3.900	4.100	3.900	4.000
H2 storage	3.771	3.608	3.767	3.417	3.450	3.683	3.883	3.808	3.717	3.642	3.842
Submarine mining	2.063	2.258	2.100	2.350	2.317	2.117	1.950	1992	2083	2.125	1.958
Natural H2	3.604	3.008	3.433	3.083	3.283	3.750	4.017	3.975	3.950	3.908	4.175
Helium	3.292	3.450	3.333	3.433	3.367	3.233	3.167	3.183	3.167	3.183	3.117

The sensitivity analysis considering alternative weighting schemes reveals important trade-offs:

When technical–operational synergies are strongly prioritized (Scenarios A and *B*, with 50% and 40% weight assigned to Dimension I), CO_2-EOR and CCS become the most competitive alternatives, achieving scores above 4.2. This result reflects the strong compatibility of these options with existing oil and gas infrastructure, operational know-how, and subsurface asset utilization. Geothermal energy also remains highly ranked under these scenarios, indicating robust performance across technical criteria.

When economic and market factors receive greater emphasis (Scenarios C and D, with 50% and 40% weight assigned to Dimension II), lithium extraction emerges as one of the leading alternatives, while geothermal energy maintains the highest overall scores. This suggests that lithium benefits from favourable market prospects and economic attractiveness, whereas geothermal energy combines strong economic performance with advantages in other dimensions.

When strategic alignment becomes the dominant criterion (Scenarios E to J, with 40% to 50% weight assigned to Dimension III), geothermal energy consistently ranks first, while natural hydrogen gains a substantial competitive advantage, increasing from 3.60 in the base case to as much as 4.18 in Scenario J. This indicates a strong alignment of these alternatives with long-term energy transition objectives and future resource development strategies.

Finally, when sustainability considerations are jointly emphasized with strategic alignment (Scenarios F, G, and J, where Dimensions III and IV together account for 70% to 80% of the total weight), natural hydrogen becomes the second-highest ranked alternative, surpassing CCS, CO_2-EOR, and lithium extraction. This highlights the importance of decar-

bonization potential and broader sustainability benefits in enhancing the attractiveness of emerging low-carbon opportunities.

Across all weighting combinations, geothermal energy exhibits the greatest robustness, consistently achieving the highest score (3.90–4.37) and remaining the top-ranked alternative regardless of weighting assumptions. In contrast, submarine mining remains the lowest-ranked option in every scenario, indicating limited compatibility with the evaluated dimensions and low sensitivity to changes in weighting schemes.

Given these considerations, and acknowledging the influence of methodological assumptions on the final rankings, the proposed compatibility matrix should be regarded as a flexible strategic screening tool, intended to support the preliminary evaluation and prioritization of opportunities. Its application can be tailored to specific project contexts and objectives, and it should be complemented by detailed technical–economic feasibility studies, quantitative risk analysis, and site-specific evaluations in subsequent decision-making stages.

5. Discussion

5.1. Theoretical Contributions and Strategic Implications

This study proposed the concept of Co-exploration as a diversification and integration strategy for the O&G Exploration and Production segment in the energy transition context. The central contribution lies in constructing a conceptual framework that expands the traditional scope of hydrocarbon exploration to include joint prospection and development of alternative subsurface resources, leveraging technical–operational synergies, legacy geological and geophysical data, existing infrastructure, and accumulated O&G industry competencies.

Co-exploration distinguishes itself from related concepts such as super basin (AAPG), super resource basin, and simple diversification or retrofit strategies by proposing exploratory integration from project conception, not merely as revisiting or subsequent utilization of mature assets. While the super basin concept focuses on hydrocarbon maximization in mature basins, and super resource basin suggests coexistence of multiple energy resources in low-carbon hubs, Co-exploration expands geographically to include frontier basins and emerging areas, and temporally by proposing integrated decisions and optionality from initial exploration phases.

Traditionally, O&G Exploration operates under a risk framework dominated by geological uncertainties, commodity price volatility, and project execution challenges. However, the acceleration of the energy transition introduces new layers of complexity: market risks (demand peak, long-term projection volatility), regulatory risks (carbon pricing, licensing constraints, supply limitation initiatives), financial risks (ESG fund divestment, restricted capital access), technological risks (disruption by electrification and renewables), and reputational and legal risks (climate litigation, stakeholder pressure). This study systematized these risks into five main groups, demonstrating how they intersect and amplify decision uncertainties in the upstream segment.

Facing this scenario of expanded and interdependent risks, Co-exploration offers an alternative combining risk mitigation, strategic optionality creation, and preservation of geoscientific competencies. By proposing integrated exploration of alternative resources with potential to generate value uncorrelated to hydrocarbon markets, the strategy seeks to: (1) diversify revenue sources, reducing exclusive dependence on oil and gas prices; (2) increase portfolio flexibility, incorporating real options logic; (3) reduce marginal exploration costs, leveraging legacy data and existing infrastructure; (4) mitigate stranded asset risks; and (5) preserve Exploration relevance, repositioning geoscientists as subsurface solution integrators.

The Compatibility Matrix (Table 3) offers an analytical tool for qualitative assessment of alternative resources according to eleven structured criteria. In the baseline scenario in which no specific weights are assigned to the criteria or their dimensions, the matrix reveals that geothermal energy (EGS) and lithium in brines present the most balanced profiles for strategic integration, combining strong technical–operational synergies, expanding markets, and alignment with decarbonization objectives. Conversely, CO_2-EOR and CO_2 storage (CCS) offer the highest immediate technical synergies but lower diversification potential, while submarine mining faces prohibitive entry barriers. Natural hydrogen and helium present long-term opportunity profiles with high strategic potential but are limited by technological and market uncertainties.

Co-exploration also has implications for producing countries dependent on oil revenues. The strategy can support economic diversification efforts, leveraging infrastructure, skilled workforce, and accumulated geological knowledge to expand economic uses of the subsurface. Governments can stimulate Co-exploration through policies such as regulatory agency integration for coordinated licensing, inclusion of alternative exploratory efforts in minimum work programs, prioritization of low-carbon projects in mandatory R&D investments, attribution of points for alternative resource prospection in block auctions, and fiscal and credit incentive policies.

5.2. Practical Decision-Making Implications

The Co-exploration framework introduces several practical decision-making changes compared to existing multi-resource assessment approaches. Unlike conventional approaches that assess alternative resources sequentially or retroactively, typically after hydrocarbon exploration has concluded, Co-exploration proposes simultaneous assessment from initial exploration phases. This enables joint acquisition campaigns where seismic surveys, geochemical sampling, and well drilling are designed to characterize multiple resources simultaneously, reducing total exploration costs and accelerating alternative resource identification.

Traditional approaches generally evaluate alternative resources as standalone diversification opportunities, using sector-specific metrics and independently defined decision criteria. Co-exploration, however, incorporates these resources into the upstream portfolio from the outset, applying integrated risk–return frameworks that explicitly account for correlations among resource types, commodity markets, and O&G price trajectories. By adopting a portfolio perspective, capital allocation decisions move beyond the assessment of O&G projects and toward the optimization of overall portfolio resilience, with alternative resources potentially serving as strategic diversification assets and natural hedges against transition-related risks and market uncertainties.

This portfolio-oriented perspective extends decision-making across the entire asset lifecycle. Under a Co-exploration framework, a frontier exploration block may be prioritized not only for its hydrocarbon potential but also for the presence of complementary resources and services, such as favorable geothermal gradients, lithium-bearing brines, or suitable geological formations for CO_2 storage. Likewise, development plans for producing and mature fields can be designed to preserve future repurposing opportunities, incorporating provisions for the reuse of wells, pipelines, and processing facilities in alternative applications. As a result, Co-exploration influences not only exploration and development priorities but also decommissioning strategies, infrastructure investment decisions, and the potential extension of asset economic life beyond conventional hydrocarbon production.

The benefits of Co-exploration also extend to subsurface data management. Geological and geophysical datasets originally acquired for hydrocarbon exploration, and often regarded as sunk costs following unsuccessful campaigns, can acquire significant addi-

tional value when reinterpreted for alternative resources and storage opportunities. Seismic surveys, well logs, reservoir models, and basin studies may provide critical insights for geothermal development, critical mineral extraction, hydrogen storage, or CO_2 sequestration. Consequently, Co-exploration reshapes decisions regarding data acquisition strategies, long-term data preservation, reprocessing investments, and data-sharing agreements. Rather than serving a single exploration objective, subsurface datasets become strategic multi-purpose assets capable of supporting successive resource opportunities and enhancing the long-term value of exploration investments.

Co-exploration also reshapes interactions with governments and regulators by encouraging integrated licensing approaches, coordinated work programs, and incentive mechanisms that recognize the development of multiple subsurface resources. This shifts the focus from hydrocarbon production alone toward broader contributions to energy security, decarbonization, and long-term resource stewardship.

Synthetically, the Co-exploration strategy transforms resource assessment from a sequential, hydrocarbon-centric process into an integrated, optionality-driven framework that systematically incorporates alternative resources into upstream strategy from project inception through decommissioning.

5.3. Limitations and Strategic Challenges

Despite potential advantages, the Co-exploration strategy faces significant structural and operational limitations:

Contextual heterogeneity: The suitability of each resource varies significantly across sedimentary basins, tectonic regimes, national regulatory frameworks, and existing infrastructure. The matrix does not capture these specificities.

Spatial trade-offs (resource bias): Co-exploration guided exclusively by optimal O&G criteria tends to test alternative resources under suboptimal conditions, since the best geological occurrences of geothermal energy, natural hydrogen, lithium in brines, or geological storage do not necessarily coincide with the best hydrocarbon *plays*. This bias may distort viability assessments of alternative resources.

Regulatory and fiscal asymmetry: Historically, the O&G sector benefits from special tax and customs regimes that do not apply to alternative resources, even when sharing technologies, equipment, and logistics. This asymmetry creates internal competitiveness distortions in corporate capital allocation decisions.

Internal capital competition: Alternative resources compete with O&G projects for capital, human resources, and operational priority in an environment strongly favorable to the incumbent segment, which has mature assessment metrics, consolidated infrastructure, established markets, and high return expectations. Emerging alternatives tend to present lower return expectations, longer payback, and dependence on long-term contracts, government incentives, and construction of specific supply chains, elevating risk perception.

Greater operational complexity: Integration of multiple resources introduces new sources of technical uncertainty, requires coordination between operational, environmental, legal-regulatory, and commercial areas, and demands professional requalification and development of new competencies through partnerships with academia, other O&G companies, and technology, utilities, and chemical/mineral industry sectors.

Synergy materialization uncertainty: Potential advantages of Co-exploration depend on effective materialization of assumed synergies (infrastructure sharing, data reuse, marginal cost reduction). If these synergies do not materialize as expected, integration costs may exceed benefits.

Upside renunciation: The Co-exploration strategy implies renouncing part of maximum return in scenarios very favorable to O&G, trading upside potential for long-term robustness and resilience.

The Compatibility Matrix, therefore, functions as an initial strategic screening tool, guiding the prioritization of alternative resources for exploratory integration. Moreover, it can be adapted and customized according to the organization's criteria, allowing the assignment of different weights to the evaluated factors in line with their specific characteristics, organizational strategies, and business objectives, thus becoming a flexible instrument aligned with the particular needs of each context. However, it must be complemented and followed by in-depth technical–economic feasibility analyses, operational synergy modeling, specific risk assessment, and alignment with long-term corporate and national objectives.

6. Conclusions and Future Research Agenda

This study systematized the concept of Co-exploration as a strategic response to the challenges and uncertainties imposed by the energy transition on the O&G Exploration and Production segment. The conceptual framework developed demonstrates how technical–operational synergies, accumulated geoscientific competencies, legacy data, and existing infrastructure can be leveraged to diversify exploratory portfolios beyond hydrocarbons, creating strategic optionality and enhancing long-term resilience.

The analysis of five categories of alternative subsurface resources—geothermal energy (EGS), lithium in brines, submarine mining, natural hydrogen/helium, and geological CO_2 storage—revealed distinct integration potential profiles with O&G Exploration. The Compatibility Matrix developed offers practical guidance for prioritizing resources according to geological synergy, data utilization, technical–operational compatibility, infrastructure sharing, technological maturity, market expectations, capital intensity, risk reduction potential, strategic alignment, political-regulatory support, and environmental–climate–social suitability.

Key findings indicate that geothermal energy and lithium in brines present the most balanced profiles for immediate strategic integration, combining high technical synergies with expanding markets and alignment with decarbonization objectives. CO_2 storage (CCS) offers the highest operational synergies with O&G but lower diversification potential. Natural hydrogen represents a long-term strategic opportunity with high potential but limited by technological and market uncertainties. Submarine mining, despite strategic appeal, faces prohibitive environmental, regulatory, and economic barriers in the short and medium term.

The Co-exploration strategy also presents important implications for producing countries dependent on oil revenues, offering a pathway for economic diversification that leverages existing infrastructure and skilled workforce. However, the strategy's effectiveness depends on overcoming significant challenges, including spatial trade-offs (suboptimal resource testing), regulatory and fiscal asymmetries, internal capital competition, operational complexity, and synergy materialization uncertainty.

Future Research Directions

The conceptual framework proposed opens multiple avenues for future research:

Conceptual refinement and operationalization: Elaborating more precise definitions distinguishing Co-exploration from related concepts, developing specific metrics and indicators for synergies and flexibility, and constructing Co-exploration typologies for different contexts.

Business models for co-development: Comparing different organizational structures (internal development, joint ventures, venture capital, partnerships, hub models) and their

suitability for different alternative resources, analyzing how each arrangement distributes resources, risks, and competencies.

Quantitative modeling and multi-resource portfolio analysis: Developing stochastic models (Monte Carlo simulation, real options) to compare economic viability and risk profiles of traditional versus integrated projects. Extending analysis to multi-resource portfolio optimization models incorporating multiple alternatives simultaneously, evaluating trade-offs among expected return, adjusted risk, capital constraints, ESG criteria, and decarbonization targets. Investigating temporal dynamics of capital allocation over multi-decade cycles, incorporating learning, strategy adjustments, and strategic optionality under deep uncertainty.

Spatial and geographic analysis: Developing explicit spatial analyses of Co-exploration potential in specific basins, mapping multi-resource occurrences and evaluating spatial trade-offs between optimal areas for O&G versus alternative resources.

Risk and deep uncertainty analysis: Modeling deep uncertainties using robust decision-making approaches, analyzing qualitative energy transition scenarios, and investigating correlations and interdependencies between different risk categories.

Public policy and regulatory assessment: Evaluating the effectiveness of policy instruments to stimulate Co-exploration, conducting international comparative analyses of regulatory frameworks, and investigating institutional arrangements for multi-agency coordination.

Empirical validation: Conducting detailed case studies of existing integrated resource exploration projects, interviews with industry professionals and policymakers, and econometric analyses of company performance comparing diversification strategies.

Socio-environmental dimensions: Investigating and comparing socio-environmental impacts between traditional and integrated projects, analyzing stakeholder perceptions and social acceptance, and developing integrated sustainability metrics aligned with UN Sustainable Development Goals.

Multi-criteria Analysis (MCA) refinement: This study already applies an equal-weighting MCA baseline complemented by a ten-scenario sensitivity analysis. Future work could explore non-linear aggregation methods and empirically derived (e.g., expert-elicited) weighting schemes to further refine the framework, thereby providing greater flexibility and enabling its application in specific decision-making contexts.

These research extensions would transform Co-exploration from a conceptual proposition into an operational tool for strategic planning and capital allocation, supporting E&P companies and producing countries in navigating the complexities of the energy transition while maintaining energy security and creating long-term value. The strategy's success depends on coordinated efforts from industry, governments, academia, and civil society to develop the necessary technical, institutional, regulatory, fiscal, and market conditions for viable and sustainable implementation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources15110143/s1, Supplementary Material SI—Weight combinations assigned to the dimensions of the compatibility matrix considered in the sensitivity analysis, including an equal-weighting baseline as a neutral starting point. Supplementary Material SII—Sensitivity analysis results based on ten different weight scenarios assigned to the compatibility matrix dimensions.

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Abbreviations

The following abbreviations are used in this manuscript:

AAPG	American Association of Petroleum Geologists
AGS	Advanced Geothermal System
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CLGS	Closed-Loop Geothermal System
CO_2	Carbon Dioxide
DLE	Direct Lithium Extraction
E&P	Exploration and Production
EGS	Enhanced Geothermal System
EOR	Enhanced Oil Recovery
ESG	Environmental, Social, and Governance
ETS	Emissions Trading System
G&G	Geological and Geophysical
H_2	Hydrogen
He	Helium
HPHT	High-Pressure, High-Temperature
IEA	International Energy Agency
IOCs	International Oil Companies
ISA	International Seabed Authority
M&A	Mergers and Acquisitions
NEA	National Energy Administration (China)
O&G	Oil and Gas
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Operational Expenditure
R&D	Research and Development
REPETRO	Special Customs Regime for Export and Import of Goods Intended for Exploration and Production Activities (Brazil)
ROVs	Remotely Operated Vehicles
TRL	Technology Readiness Level
UN	United Nations

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