ARTICLE INFO
Received : April. 23, 2020
Revised : March 8, 2021
Accepted : June. 23, 2021
CT&F - Ciencia, Tecnologia y Futuro Vol 11, Num 1 June 2021. pages 97 - 108
DOI : https://doi.org/10.29047/01225383.253

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CRITICAL FACTORS FOR UNCONVENTIONAL HYDROCARBON RESOURCES DEVELOPMENT

FACTORES CRÍTICOS PARA EL DESARROLLO DE HIDROCARBUROS NO CONVENCIONALES

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ABSTRACT

Countries all over the world struggle to exploit their Unconventional Hydrocarbon Resources (UHR) to secure energy supply, but only a few of them have succeeded. Regulators and decision-makers should understand the critical factors required for companies to attract capital, technology, and good practices to promote innovation and generate the virtuous cycle that translates into sustainable production. This study seeks to identify the most relevant factors for UHR commercial development. We assessed the UHR exploiting state in 60 countries and identified the critical common development factors for the 22 that are most active. The proposed Unconventional Hydrocarbon Development Index (UDI) allows to model, rank, benchmark, and forecast UHR development activity for any given country. We focused on the case of Colombia to illustrate the validity of this Index. Evidence suggests countries where National Oil Companies (NOCs) address the challenge of exploiting UHR on their own, may lack the required expertise, despite having governmental support and capital availability. It is easier for them to emulate resilient North American firms exploiting UHR by partnering with them to effectively incorporate best practices Governments can facilitate the process through UHR support, surface and subsurface risk reduction, a proper tax regime, and ESG practice promotion.

RESUMEN

Muchos países alrededor del mundo realizan ingentes esfuerzos para explotar su recurso hidrocarburífero no convencional con el fin de asegurar la autosuficiencia, pero pocos han sido exitosos. Los reguladores y tomadores de decisión requieren comprender los factores críticos necesarios para atraer empresas petroleras multinacionales, con el fin de que apalanquen los esfuerzos de las empresas petroleras nacionales, a través de las mejores prácticas, recursos de capital y la tecnología, necesarios para lograr la innovación y así poder desarrollar estos abundantes recursos de manera ambiental y generando utilidades. El objetivo principal de este estudio es identificar los factores críticos de éxito más relevantes para el desarrollo de estos recursos. Para esto, se analizaron los resultados de 60 países e identificaron los factores críticos en común de los 22 más activos. Se propone la utilización del Índice de Desarrollo de Hidrocarburos no Convencionales (UDI) que utiliza estos factores para modelar, ordenar, comparar y pronosticar la actividad de desarrollo del potencial hidrocarburífero no convencional para un determinado país en particular. Se evalúa el caso de Colombia con el fin de mostrar la validez del Índice. Los resultados del estudio sugieren que aquellos países en donde la empresa petrolera nacional realiza los esfuerzos para desarrollar estos recursos por su cuenta, carecen del conocimiento y la experiencia requerida, a pesar del apoyo gubernamental y la disponibilidad de recursos financieros. Las posibilidades de emular el desempeño de las empresas resilientes norteamericanas que explotan los recursos hidrocarburíferos no convencionales mejoran al realizar alianzas para incorporar las mejores prácticas de manera más efectiva. Los gobiernos pueden apalancar el proceso mediante el apoyo al desarrollo de los Yacimientos no Convencionales, la reducción de los riesgos de superficie y subsuelo, un régimen fiscal atractivo y el apoyo de las prácticas ESG.

KEYWORDS / PALABRAS CLAVE

Shale gas development | Unconventional oil and gas development | Critical factors | Innovation | International oil companies | Resilience.

Desarrollo de gas de esquisto | Desarrollo de petróleo y gas en yacimientos no convencionales | Factores críticos | Innovación | Empresas petroleras multinacionales | Resiliencia.

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1. INTRODUCTION

Global primary energy demand would rise by 1.3% every year until 2040, not considering the post-Paris Agreement. The share of fossil fuels in world energy demand was 81% in 2018, but with the current policies it reduced slightly to 79% in 2030 and 78% in 2040. Countries make permanent efforts to avoid energy dependence on entities abroad to develop reliable sources of energy. The preferred alternative to meet this demand growth is natural gas, increasing its share in the energy basket. It translates into cleaner burning and reduces air pollutants and greenhouse gas (GHG) emissions, compared with other fossil fuels. Consequently, there has been a significant switch from coal to gas for electric generation, mainly in the US, Europe, and China (1).

UHR constitutes an abundant, reliable source to satisfy the growing world energy needs. UHR is available in nearly 60 countries, and despite the challenges involved, at least 32 of them have started exploration and development activities for its exploitation (2).

The main benefits from Unconventional Oil and Gas Development (UOGD) include energy security, switching coal to gas for electricity generation to reduce GHG emissions, revenues, new jobs, local business opportunities, and improvement to social wellbeing at large. The drawbacks are local environmental and global clime effects, unequal distribution of risks and rewards, energy transition delay, and public controversy (3). The decision for a country to move toward UOGD can be assessed based on the Analytic Hierarchy Process (AHP), which involves balancing the benefits and opportunities with the costs and risks involved (4). The decision to opt for exploiting shale gas as compared to nuclear energy or maintaining the prevalence of coal for electric generation in Poland represents a comprehensive case (5).

There is commercial success when oil companies are keen to develop hydrocarbon resources and apply best practices to build a learning curve, reduce costs, and increase productivity, as it is the only way to have profitable green exploitation. In the early 2000s, the return on capital for the IOCs was near 20%. In 2019, it more than halved, considering the same level of hydrocarbon prices. Hence, more challenging conditions exist to exploit UHR in the US and Canada after 2019 as investors started to demand better equity returns, debt reduction, and increasing Environmental, Social, and Governance (ESG) goals to obtain or boost their Social License to Operate (LTO). Oil and Gas (O&G) companies started to switch their focus from growth to productivity and defined aggressive ESG goals to reduce GHG emissions and freshwater consumption.

Additionally, lower oil and gas prices fuelled by increased production, COVID-19 pandemic, and a lower world energy demand, added to restrictions on building new infrastructure due to public protests, affected IOCs' financial results possibilities to invest in UOGD. Resilient firms were those with stronger balance sheets, lower debt, productivity, and diversified assets. Only a few of them had antifragile behavior and could grow production in 2020 despite all these challenges (6).

Consequently, governments should be aware of the increasing need to enforce environmental protection and establish a fiscal regime allowing for reasonable returns to potential investors. Policymakers must understand the critical factors required for successfully exploiting UHR, incorporating investor needs by reducing and controlling non-technical risks and uncertainties to satisfy their possibility of attaining minimum profit. Such is the case of Argentina, Oman, Saudi Arabia, the United Arab Emirates (UAE), and Bahrain, which invested in advance in exploration and infrastructure to become more appealing as compared to other countries.

Numerous studies have focused on the technological, environmental, or economic aspects of UHR development. Only a few assess the critical factors at the country level for UOGD. This paper takes a step further and explores all those factors at a nation's level to attain commercial UOGD. Hence, this study hypothesis suggests that a country can only exploit its UHR potential after improving the key factors required for UOGD. We tested this hypothesis focusing on the 22 nations that have pursued UOGD and the main factors required to obtain commercial production through projects and final investment decisions (FID) from NOCs and IOCs.

This study has a twofold goal. First, review a country's current UHR development stage, and then assess its possibilities of success. We analyzed the country's reasons and the main aspects to be addressed to achieve commercial production. The aim is to assess the current situation and the main aspects of commercial exploitation to support dialogue among regulators and energy decision-makers. The proposed UDI enables the assessment and benchmarking among countries involved in UOGD, offering a convenient way to evaluate the possibilities of success for a given country, considering those critical factors. Second, analyze the case study of Colombia to provide further insights, considering the current status and the aspects the country needs to improve to explore, develop, optimize, and generate commercial UHR development. By overcoming the main barriers, the country would avoid becoming a net hydrocarbon importer in coming years.

2. STATE OF THE ART

Technical, environmental, social, and financial uncertainties are different for UOGD when compared to conventional hydrocarbon development. This section considers those distinctions and explores two different areas that provide the required context for this study: (i) UHR resource balance for regions and countries, and (ii) unconventional development factors.

UNCONVENTIONAL POTENTIAL

Hydrocarbon composition is equal in conventional and unconventional reservoirs. There are seven types of UHR: tight oil, tight gas, extra-heavy oil, coal bed methane (CBM), shale gas, oil sands (natural bitumen or tar sands), oil shale, and gas hydrates (methane hydrates). **Figure 1** depicts the different hydrocarbon reservoirs, considering the size of the deposits, costs, environmental impact, and level of technology required for development (7). UHR are located worldwide in 476 formations and 363 oil and gas basins in 60 countries. The recoverable oil resources in the world account for 30,855x10^8 barrels (billion barrels, Bb) and 6,900x10^{12} cubic feet (trillion cubic feet, Tcf) of natural gas, excluding gas hydrates (2, 8).

The UHR with the highest possibilities to develop are extra-heavy oil, tight gas and oil, gas shale, and CBM (colliery gas or coal seam gas). There is not a strict definition of extra-heavy oil and oil/tar sands. For this study, we adopted the World Energy Council definition

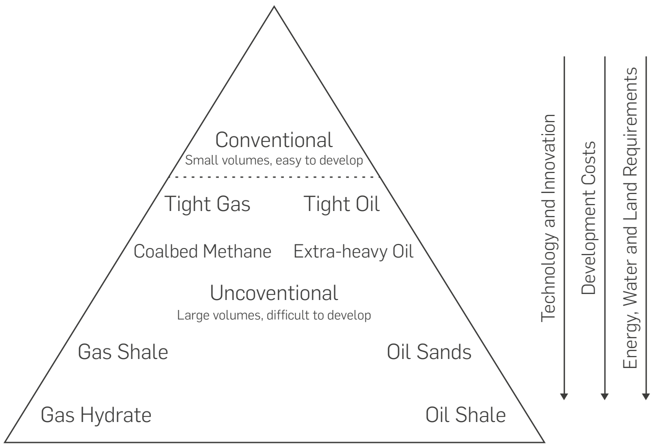

Figure 1. Hydrocarbon reservoir classification (7), adapted by the authors.

Table 1. Countries with the highest shale gas and tight oil resources (11).

World Shale Resources			
Country	Wet shale Gas (Tcf)	Country	Tight Oil (Billion barrels)
China	1115.2	US	78.2
Argentina	801.5	Russia	75.8
Algeria	706.9	China	32.2
US	622.5	Argentina	27.0
Canada	572.9	Libya	26.1
Mexico	545.2	United Arab Emirates	22.6
Australia	429.3	Chad	16.2
South Africa	389.5	Australia	15.6
Russia	286.5	Venezuela	13.4
Brazil	244.9	Mexico	13.1
United Arab Emirates	205.3	Kazakstan	10.6

for extra-heavy oil and oil sands: any liquid petroleum or sands containing it, with API gravity below 10° and reservoir greater than 10,000 centipoises (9).

Technically recoverable shale oil and shale gas resources amount to 7,576.6 Tcf of natural gas and 418.9 Bb of oil for 46 countries (10). **Table 1** lists the countries with the highest shale gas and tight oil resources.

It is difficult to forecast which countries will develop their UHR potential, given the challenges involved. **Figure 2** shows technically recoverable tight oil, CBM, and shale gas resources for those countries with higher chances to exploit UHR. This study incorporates the 2015 EIA UHR balance and evaluates those countries with real possibilities of UOGD, from which only Argentina and Turkey had fulfilled the expectations by 2020 (11).

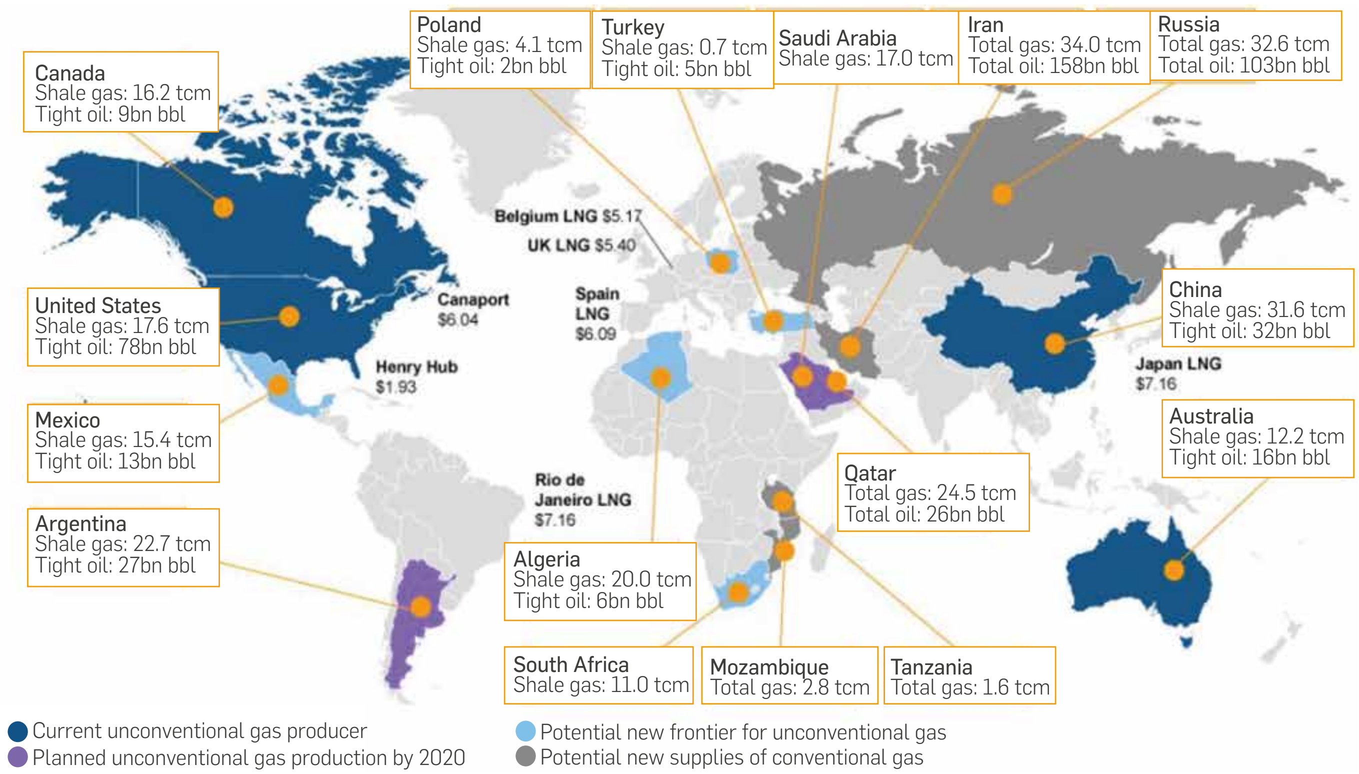

Figure 2. World countries with greater potential for exploring unconventional hydrocarbon (12).

The global heavy oil potential encompasses 7,265.3 Bb of heavy oil and 3,674.2 Bb of oil sands. Technically recoverable resources are 929 Bb and 470 Bb, respectively, scattered across 69 heavy oil and 32 oil sand basins. Countries with existing production are Canada, Venezuela, the US, China, Mexico, and Colombia. The additional highest potential is located mainly in Russia, Kazakhstan, and Saudi Arabia (13).

Oil shale exploitation concentrates in Estonia and Jordan. Production requires mining and heating the rock to later process the retort to obtain oil from the kerogen. This process is costly and consumes much energy. Countries with the highest potential for oil shale production are the US, Australia, Brazil, Russia, and the Democratic Republic of Congo (14).

The US, Canada, and Australia are the countries with the most significant UHR production. US shale oil and gas output possibly will surpass Russia's production by 2025. The US may be attributed 85% of the increase in oil and 30% of gas production until 2030. Hence, OPEC and Russia's influence in the world hydrocarbon production would reduce by 47% in 2030, from 55% in the mid-2000s (1).

UNCONVENTIONAL COMMERCIAL DEVELOPMENT FACTORS

The US, Canada, and Australia are innovators offering proper conditions for the CBM, heavy oil, tight oil, and shale gas exploitation. Only a few countries bear a resemblance to them. Heavy oil is produced mainly in Venezuela and oil shale in Estonia since several years ago thanks to solo efforts.

It is difficult to establish a cause-effect relationship between the possible explanatory factors for UHR commercial exploitation for countries other than the three (3) innovators. Argentina, Oman, Chile, and Turkey are current examples of countries able to exploit their commercially tight oil and shale gas resources. On the other hand, Russia, Saudi Arabia, India, Algeria, Poland, and China, among others, have failed despite their UHG potential and efforts.

Several studies identify critical aspects and possibilities for UOGD outside the US and Canada and conclude that economic development viability is doubtful. Accenture established eight (8) critical factors affecting the development of shale gas: (i) Size of potential resources, (ii) Enabling fiscal regime, (iii) Geology, (iv) Land access and operability, (v) Unconventional services sector, (vi) Oil and gas distribution network, (vii) Conventional and other competition, and (viii) Skilled workforce (14). The fiscal regime factor is more advantageous for IOCs in China, Russia, South Africa, and Mexico, which offer the most generous tax breaks and other incentives for shale development (15).

Researchers have also analyzed and compared specific regions and countries with the US UOGD. In China, the environmental risks and public opinion are not relevant; however, technology, gas price, and infrastructure are critical (16). A comparison between Eagle Ford development and Mexico shows a 25% cost increase and a fiscal regime that offers competitive terms to make UOGD economically feasible (17).

Europe and China require more advanced technologies, making the US experience unlikely to replicate. Six critical factors are identified: (i) Policy and regulation; (ii) People's acceptance; (iii) Infrastructure and market; (iv) Geological and natural conditions; (v) Technical and technological; and (vi) Other (18).

Similarly, geological, technological, regulatory, and public acceptance factors restrain the possibility of shale development in the EU (19). Local infrastructure, market liquidity, and drilling and completion capabilities were emphasized as critical drivers to develop resources in China, Poland, Saudi Arabia, and Algeria (20, 21).

The situation in Russia is different because most UHR is located in remote areas far from populated centers, without private land ownership. Therefore, public acceptance is not a critical factor. Nevertheless, the unavailability of infrastructure, taxation, and technology deter IOCs from pursuing UOGD in the country (22).

Today, investors request cash returns over production growth and excessive debt burden. However, surface risks are more demanding. Production rise in Canada, the US, and Argentina led to local infrastructure constraints relative to transportation and water and gas handling issues, increasing carbon dioxide (CO_2) and methane emissions due to additional venting needs. These impair producers' reputation, while increasing costs and price differentials.

People's acceptance, environmental, technological, and innovation aspects started to be more relevant after 2017, reflecting the widely spread environmental concerns (18, 23). After several years of UHR exploitation, water consumption and disposal became a sensitive critical factor that triggered public protests and generalized opposition. 31% of global shale resources are located in water-stressed regions, which would expand to 44% with UHR development. The most restricted areas are China, Algeria, Australia, Egypt, Libya, the US, Mexico, Pakistan, and South Africa. By contrast, in 51-74% of shale areas where water is available, UOGD would consume less than 1% of local water (24).

Infrastructure constraints, technology availability, environmental and social pressure have become critical factors for UOGD. Additionally, IOCs are under the scrutiny of the stakeholders, which demand increasing returns, ESG goals commitment, and lower surface risks. The weaker oil and gas prices that reflected the hydrocarbon oversupply and reduced world fossil energy demand narrow the number of countries and companies willing to execute UOGD projects.

As mentioned before, it is necessary to identify the new factors in developing UOG that are not reflected in the literature, requiring updating current studies to offer more conclusive results.

3. EXPERIMENTAL DEVELOPMENT

Observing the UHR exploiting efforts in 60 countries with notably unconventional hydrocarbons potential led us to classify them in six (6) different categories. We selected the eight (8) most representative factors from the literature review and IOCs' current investment activity. We analyzed and graded the results for the 22 countries with greater UHR development activity, considering current Final Investment Decision (FID) and production. We integrated the results based on the proposed UDI, which allows modeling the countries assessed for ranking, benchmarking, and forecasting purposes. It also offers the possibility to simulate variations in critical factors for any studied nation and evaluate its behavior and opportunities to achieve commercial success.

The US Internal Revenue Service defines IOC as a producer with no more than $5 million in retail sales of oil and gas in a year, or not refining more than 75,000 barrels of oil per day in a given year. For this paper, IOCs are Global Majors, International Independents, and Local Independents in any given country. Because of the significant number of O&G companies in the US and Canada, we only considered IOCs with production above 500 equivalent barrels of oil per day in 2019.

We narrowed the analysis to the UOGD IOCs operators in the US and Canada with market capitalization above $1 billion on December 31st, 2019. In the other 20 countries, UOGD IOC operators include companies executing exploration, development, and production activities. We obtained IOC and NOC financial data from the GuruFocus web page and operational data from Woodmac Upstream Data Tool.

COUNTRY SELECTION AND CLASSIFICATION

This paper analyses the UHR development situation of the countries with UHR potential identified through the literature review discussed in section 2.1. To evaluate each country's current UOGD level of activity, we collected data and information from different sources, including academic publications, grey literature, news from companies' web pages, and the media. We dismissed six (6) countries for their lack of reliable, updated information.

We selected the 60 nations with available updated information. We classified them into six (6) categories: Not interested, Banned or Licenses Rejected, Lack LTO, Exploration (Preliminary Studies, Exploration Activity, and Exploration Failure), Uncommercial Development (UD), and Commercial Development (CD). The last could be either Innovators or Successful Followers (22, 25).

We selected a representative sample of 22 countries from the Lack LTO, Exploration, UD, and CD categories, considering those with the most significant UHR development efforts. Despite being in the Banned group, we included the UK and Mexico as they conducted exploration studies and pilots before prohibition decisions. We also included Jordan as a successful case of shale oil development, given its current results.

CRITICAL FACTOR DEFINITION

A utility function helps measure IOCs' choice behavior incorporating the main drivers leading to the decision to invest in a specific country. They consider economic, uncertainty preferences, and trade-offs. Those factors differ depending on each country's specific strengths and needs. It was necessary to identify the factors shared by all countries to capture meaningful experiences to then build a model that will allow performing forecasts and sensitivity analysis. The factor identification was based on the literature review in section 2.2, considering investment efforts for the 22 selected countries.

The aim was to choose the factors that influence IOC and NOC investment decisions to exploit UHR potential. With about 9,000 IOCs, the US is the country that represents the ideal enterprise mix for UOGD.

Available infrastructure, government, regulatory, financial, and economic conditions offer the business climate required to promote the entrepreneurial spirit that fosters collaboration, innovation, and antifragility. Canada is the closest example, but limitations in infrastructure and attaining permits hinder UOGD. Other countries like Australia and Russia have multiple IOCs because of their outstanding business climate and resource potential. However, current production is their priority, and as a result, additional UHR development is a mere future possibility. Poland, India, China, and Saudi Arabia have successfully attracted IOCs, which have drilled several wells, but geological, cost, and regulatory factors have deterred their UOGD investment efforts. UK, Mexico, and Algeria are among the countries attracting IOCs for conventional hydrocarbon exploitation, but they lack LTO and government support for UOGD exploration activities.

STANDARD VALUES ESTABLISHMENT AND GRADING

We graded the eight (8) selected critical factors by analyzing actual UOGD results for each country, avoiding considering firms' announcements or expectations. We dismissed NOCs activities, the volume of production, and total investment because they do not necessarily reflect the number of IOCs or the current level of activity. We attempted to reduce subjectivity by using parameters drawn from the recognized 2019 Global Innovation Index (GII). Thanks to their utilization, it will be possible to update UDI computations quickly and transparently in the following years.

The GII parameters evaluated are Institutions, Political Environment (Regulatory and Business Environment), Environmental Performance (Climate & Energy), Human Capital & Research (Education, Tertiary Education, and R&D), Infrastructure (Information & Communication Technologies, General Infrastructure, and Ecological Infrastructure), Market Sophistication (Credit, Investment, and Trade, Competition & Market scale), Business Sophistication (Knowledge workers, Innovation linkages, and Knowledge absorption), Knowledge and Technology Outputs (Knowledge Creation, Impact, and Diffusion), Creative Outputs (Intangible assets, Creative goods & services, and Online creativity).

The selected GII parameters offering statistical significance to the UDI results are Political Environment, Environmental Performance (Climate & Energy), General Infrastructure, Knowledge workers, Knowledge absorption, Business sophistication, and R&D.

The factor grading reflects the actual results from the UOGD activity and the parameter GII scores. We utilized the Delphi method and a three-point scoring grading scale to facilitate the analysis, limited to either (1, 3, or 5) reflecting a poor, average, or excellent performance. Additional to simplicity, it avoids arbitrariness, spurious results, and non-comparable scorings.

UNCONVENTIONAL HYDROCARBON DEVELOPMENT INDEX

The UDI is a model to incorporate the main factors that explain the successful commercial development of UHR around the world. Integrating the results from the 22 nations actively involved in this effort provides a means to identify key aspects to ponder and forecast potential results. It is also a vehicle to test the hypotheses. The proposed UDI model summarizes the results facilitating the ranking and benchmarking of the analyzed countries. It also allows modeling the critical factors for any of them and forecast their behavior and possibilities to achieve commercial success.

The UDI uses actual results for the analysis, considering nation-specific needs and infrastructure limitations. The UOGD level varies from a one (1) to five (5) score grading. Hence, UDI scores classified the analyzed countries within five categories:

Commercial development innovators: scores higher than 4.5.
Commercial development followers: scores greater than 4.0 and less than or equal to 4.5.
Uncommercial development: scores higher than 3.5 and less than or equal to 4.0.
Exploration: scores higher than 3.0 and less than or equal to 3.5.
Lack of LTO or exploration failure: scores less than or equal to 3.0.

UDI procedure mimics the theoretical value from a multivariate analysis. Adaptive Conjoint Analysis (ACA) is the statistical method generally utilized to decompose consumer preferences into product features' partial contribution. It offers a way to explain the choices for specific products, simulate preferences for new ones, or modify critical factor scores to determine the decisive factors' weights (26). A helpful analogy is to treat IOCs and NOCs as consumers, products as countries, factor weights as part-worth, and scores reflecting the attributes' quality.

To collect the information required for the study, we tabulated investors' decisions to enter or leave a country reflected in the UDI, avoiding bias and respondent's simplification difficulties common to marketing research. We followed a trial and error approach for the UDI modeling and the ACA logic to find the critical factor weights, considering the actual UOGD results for the 22 analyzed countries.

4. RESULTS

The analysis and the grading of the selected critical factors allowed us to collect and compute the UDI score to rank the 22 studied countries, as described in section 3.

COUNTRY CLASSIFICATION

There is a wide UHR development range among the 60 analyzed countries, with less than 22% reaching commercial development (27). The case of shale (tight oil, tight gas, and gas shale) reduces to 11% of the 46 countries with potential, according to the EIA World Shale Resource Assessments (11). We evaluated and grouped the countries reviewed in section 2.1 in six (6) categories, considering UHR type and current development status (**Table 2**). The categories for the analyzed countries are defined as follows:

No interest: having either high conventional production, water stress, or challenging political environment to generate the minimum conditions for UOGD.

Bans, Moratoria, or License rejection: applied to hydraulic fracturing and shale exploration and development activities. License rejection involves those countries where the time to grant exploitation licenses is too long in response to public sensitivity, leading to the affected projects' suspension.

Lack of LTO: solid public opposition, which restrainins exploration activities.

Exploration: UHR potential evaluation through geological studies, surveys, pilot tests, and appraisal before funding development project approval. It can have three (3) stages: i) preliminary studies; ii) exploration activity (seismic, well drilling, pilot test); and iii) failure. There could be small quantities of hydrocarbon production during the exploration activity. Failure occurs after several exploratory wells have been drilled and, therefore, firms abandon any UHR activity. Uncommercial Development: high UHR potential with technical difficulties in exploiting, commercializing hydrocarbons, and obtaining minimum financial returns.

Commercial Development: UHR exploitation with participation from IOCs and NOCs. It divides into Innovators and Successful Followers.

Table 2. Countries with significant unconventional potential current development status.

Category	Sub Category	Shale*	CBM	Extra-Heavy Oil	Oil Shale	Gas Hydrates
No interest		Brazil, Lybia, Chad, Iran, Irak, Egypt, Pakistan, Tunisia, Qatar, Kazakhstan, Australia, Russia, Venezuela	Russia, China	Russia, China, Saudi Arabia	Uzbekistan, Republic of Congo	US, Russia, Canada
Bans, moratoria or license rejection		France, Bulgaria, Netherlands, Ireland, Denmark, Belgium, Italy, Czech Republic, Germany, Scotland, Mexico, UK		Canada		
Lack LTO		Algeria, South Africa, Romania				
Exploration	Preliminary studies	Ukraine, Hungary, Spain, New Zeland, Peru, Morocco, Jordan, Kuwait, Indonesia	Vietnam, Botswana; Indonesia		Ukraine; US, Australia; Russia, UK	Norway
	Exploration activity	Colombia, United Arab Emirates, Bahrain	Colombia		Mongolia, Morocco	Japan, China
	Exploration failure	Poland, India				
Uncommercial Development		China, Saudi Arabia, Russia	China			
Commercial Development	Innovators	US, Canada	US, Canada, Australia	US, Canada	Estonia	
	Successful Followers	Argentina, Turkey, Oman, Chile		Venezuela	Jordan, China, Israel, Germany, Brazil	

(*) Shale: tight oil, tight gas and/or gas shale.

Countries with the ability to attract IOCs to work together with their NOCs possess the minimum critical factors required for UHR commercial development. IOCs should share the best practices, technology, and capital needed to implement the trial and error approach to spur innovation, reduce cost, optimize productivity, and avoid environmental damage. Such companies, if successful, can be considered antifragile because they can operate in uncertain environments, triggering options to grow and reduce costs while complying with local regulation and ESG requirements.

CRITICAL FACTORS

We selected the critical factors and grouped them into three (3) different categories (i) Government Support; (ii) Exploration; and (iii) Commercial Development. Government support is essential to conduct any exploration activity. We utilized UDI to compute the factor weight, as described in section 3.4. We include the UHR volume as a reference. However, it is not part of the essential factors as countries like Turkey have developed their shale potential despite its comparatively small UHR potential.

Table 3. Critical Factors and weights.

Critical Factors	Weight
1. Government Support	**20%**
Political environment	5%
Conventional and Other Competition	15%
2. Exploration	**55%**
Geology	20%
Land/access, Operability & Water Stress	10%
Enabling fiscal regime	10%
Public Opinion (LTO)	15%
3. Commercial Development	**25%**
Oil & Gas Infrastructure	15%
Innovation	10%
Unconventional Development Index	100%

Table 3 shows the selected factors and their weights. Definitions and grading descriptions are adapted from the review in section 2.2 and described in the Appendix. We obtained the grading for the different factors from actual result observations from grey literature and specialized oil and gas industry reports. Political environment and Innovation factors scoring from the ranking and pillar metrics within the GII-19 Index, as described in section 3.

Factor weights obtained from UDI result in a compound average for the analyzed nations. Having equal weights enables country standardization and ranking. However, actual weights may differ for a particular country according to its internal priorities, strengths, and weaknesses. The cases studies in more depth compare the US and China actual shale gas development efforts, where factor weight differences are significant (28).

UNCONVENTIONAL HYDROCARBON DEVELOPMENT INDEX

The UDI allowed to rank the 22 studied countries, according to their grading for the eight (8) selected critical factors, based on the most reliable information regarding their efforts for UHR exploration and development. Table 4 depicts factor grading and the resulting UDI scores for each country.

5. RESULTS ANALYSIS

There are several countries in the world that are struggling to develop their UHR potential to assure energy security and enhance GDP. The few countries that have successfully developed it suggest that possessing the resource is not the only condition for an effective exploitation. We have identified the critical factors required for UOGD and modeled them to prove the need to to fulfill most of them to develop UHR.

Commercial Development Innovators, US (shale, CMB), Canada (extra-heavy oil), and Australia (CMB) reached the top UDI scores thanks to their world-class infrastructure, political environment, and innovation, among other critical factors. The Estonia (Shale Oil) and Japan (Gas Hydrates) cases are not part of this study, given their lower span. GII-19 score for all of them is in the top tier, the US (3th), Japan (15th), Canada (17th), Australia (22th), and Estonia (24th), suggesting the importance of country innovation in the early stages of UHR exploitation (23). They started activities in a less demanding ESG environment, and further research and innovation will be required to comply with the current sustainability requirements.

The cases of China, Saudi Arabia, and Russia, classified as Uncommercial Development, denote that despite the abundant UHR and the strong government and financial efforts to develop their resources, the lack of innovation is a critical factor for UOGD. China and Saudi Arabia have attracted oil service companies to bring the latest technology but missed a favorable environment to attract IOCs to lead innovation and overcome their inherent difficulties.

By contrast, Argentina, Oman, and Turkey, categorized as Successful Followers, have effectively attracted IOCs to bring in capital and spur the innovation required to reduce costs and optimize production output. They are not experiencing environmental and social demands, mostly because the shale oil fields are located close to oil and gas infrastructure in remote desertic areas with water availability. When reviewing the GII-19 innovation ranking, they rank 53th (Argentina), 86th (Oman), and 72th (Turkey), showing that innovation skills did not come up with the countries but with the IOCs. Venezuela and Canada reflect how the factors evolve with time. Two decades ago, the former successfully attracted IOCs to develop its extra-heavy oil resources jointly with the NOC, PDVSA. However, the political environment and the fiscal regime have undermined investment. In Canada, the difficulties experienced in building the necessary infrastructure to respond to the increasing production due to environmental and social concerns have impaired IOC's financial returns and equity value.

Besides Oman, UAE, Jordan, Saudi Arabia, and Bahrain are making efforts to exploit UHR by attracting IOCs, reducing surface and subsurface risks, and improving fiscal regime conditions, which is reflected in a range of UDI scores of 3.1 to 4.0. These countries exploit their advantages of land availability except for Jordan, which focuses on shale oil development. They leverage on existing oil and gas infrastructure, abundant UHR resources, government commitment, and lack of social issues. They also reduce exploration uncertainty by investing in seismic and studies and mimic Saudi Arabia's example to bring seawater to the oil and gas fields and minimize GHG emissions. Together with the tax flexibility and strong NOCs, they attract the required IOC technology and investment for UHR development.

As compared with other industries, political environment weight is not high because IOCs are accustomed to operating in harsh regions. Country risk is an issue only in situations of political or economic unrest. Such is the case of Ukraine, where despite the UHR potential

Table 4. Unconventional Hydrocarbon Development Index ranking for the 22 analyzed countries.

	US	Canada	Argentina	Australia	Oman	Chile	Turkey	Jordan	China	Russia	UK	Saudi Arabia	UAE	Vene-zuela	Bahrain	Colombia	Poland	Mexico	Romania	Algeria	South Africa	India
General Information																						
Size of potential Resources (Tight Oil) - Bb	78	9	27	16	48	2,3	5	6,8	32	103	-	-	205	167,3	167,3	7,4	2	13	50,7	6	-	
Size of potential Resources (Shale Gas) - Tcf	623	573	802	429	10,5	48,5	24,7	0,1	1115	285	26 - 130	600	22,6	13,4	13,4	54,7	145	545	0,3	707	390	96
Companies																						
Onshore Producing IOCs	68	59	22	46	1	1	9	0	22	22	17	1	0	19	19	14	0	9	3	6	0	14
UOGD Operator IOCs	37	13	8	17	2	1	1	0	0	0	1	0	0	13	13	3	0	0	0	0	0	0
NOCs	0	0	1	0	1	1	1	1	4	2	0	1	1	1	1	1	3	1	1	1	1	1
Total	37	13	9	17	3	2	2	1	4	2	1	1	1	14	14	4	3	1	1	1	1	1
Critical Factors																						
1. Government Support																						
Political environment	5	5	1	5	3	3	1	1	3	1	5	1	5	1	1	1	1	1	1	1	1	1
Conventional and Other Competition	5	4	5	5	5	5	5	5	5	3	5	5	3	3	5	3	3	5	5	3	5	3
2. Exploration																						
Geology	5	5	5	5	5	5	5	5	3	5	3	3	3	5	3	3	1	5	3	5	3	1
Land/access, Operability & Water Stress	5	5	5	5	5	3	3	5	1	5	3	3	3	5	1	5	3	3	3	1	1	1
Enabling fiscal regime	5	5	3	3	3	5	5	3	3	1	5	1	1	1	3	3	3	3	3	1	3	3
Public Opinion (LTO)	3	3	5	3	3	5	3	5	5	5	1	5	3	3	3	3	5	1	1	1	1	3
3. Commercial Development																						
Oil & Gas Infrastructure	5	5	3	3	5	1	3	1	3	3	3	3	5	3	5	3	1	3	1	3	1	3
Innovation	5	3	3	3	1	3	1	1	5	3	5	3	3	1	1	3	3	1	1	1	1	1
Unconventional Development Index	4.70	4.35	4.10	4.00	4.00	3.90	3.60	3.60	3.60	3.60	3.50	3.30	3.20	3.10	3.10	3.10	2.90	2.80	2.40	2.40	2.20	2.10

and government support, IOCs left the country after the Russian invasion and have not returned ever since.

Social and government support are critical issues for UOGD. The lack of LTO and government support have deterred the initial exploration efforts from UK, Mexico, Romania, Algeria, and South Africa, among other countries where shale development has been banned.

UDI score reflects UHR exploration and development degree of success. It positively correlates with the number of IOCs in each country (correlation coefficient=0.62 and R2=0.39), reflecting the relevance of IOCs presence in a country to have successful UOGD. Nevertheless, causality is difficult to establish. Although IOCs may spur investment, innovation, and development, reverse causality is also possible: after successful UOGD, IOCs are attracted. To overcome this issue, we considered the relationship between existing onshore IOC companies to UDI instead of IOCs devoted to UOGD.

The variation in the observations of UDI and IOCs existence stems from a confluence of the identified factors. E.g., UK, Colombia, and Venezuela, with more than 10 IOCs and a UDI, score below 3.6, with social acceptance concerns the first and political issues the former. Further, nations like Chile, Oman, Turkey, and Jordan are developing UHR thanks to the absence of geological, infrastructure, and logistic challenges that do not demand vital innovation and capital, thus making IOCs presence less necessary.

UOGD in Chile and Argentina reflects the first step toward UDI technological maturity. The ENAP-Sipetrol (Chile's NOC) and Tecpetrol (Argentinian Techint's subsidiary) ability to learn from the IOC's operators in Argentina and the United States demonstrates that the technology is not proprietary. However, it is becoming a standard industry practice. Unfortunately, we did not find a way to isolate each specific country's innovation and capital needs to compare them across the different nations involved to evaluate it more precisely.

Other than Chile and Estonia's lower-scope situations, there are no cases where NOCs have developed UHR independently. In light of such evidence, we have good reasons to expect that Follower Countries should attract IOCs to develop UHR. IOCs should bring in capital, technology, and good practices to promote innovation via trial and error and generate the virtuous cycle required to obtain green production and financial returns through operation optimization. Governments can facilitate the process through UHR support, surface and subsurface risk reduction, fiscal regime improvement, and ESG practice promotion.

Argentina's case is self-explanatory: in 2012, the NOC YPF invested US$ 920 million to drill 67 vertical wells at the Vaca Muerta basin, which catalyzed the execution of joint-venture agreements with Chevron Corp., DowDuPont, and Petronas during 2013-2015 to complete the exploration phase. Loma Campana field development after 2015, in partnership with Chevron, brought standardization, scale, and optimization to reduce costs and increase well productivity. Since 2016, horizontal drilling and the factory model are standard practices, following the US and Canada trends. By 2018, over 30 IOCs and local companies hold acreage in the area, which requires US$1.9 billion to reach full development (29),(30). YPF holds a majority position with a strong pipeline of shale projects and a partnership strategy to gain financial strength and technology to reach further cost and well productivity optimization, the business mantra to have profitable UOGD after Covid-19 pandemic. Additionally, aboveground risks weigh heavily in Argentina. Undeveloped transportation infrastructure, macroeconomic, political, and market risks are difficult to stand for IOCs. The partnership with YPF helps to handle them, which constitutes a convenient win-win situation.

RELATIVE IMPORTANCE ASSIGNMENT AND PRIORITIZATION OF FACTORS

The overall weight factor helps to rank countries willing to develop UHR. The factor weights in the UDI could vary from country to country, given their different priorities and circumstances. There are profound differences in technology, market, environmental, and social factors compared to the US in China's case (16).

The factors utilized in this study are in line with the literature listed in Section 2. However, after the difficulties experienced in several countries during the last decade, Public Opinion and Innovation are more prevalent. The EU has the strictest environmental regulation in contrast to the US and other countries. Adopting the precautionary principle has led European governments to impose restrictions on activities that may expose them to uncertain risks. Based on the Yale Environmental Performance Index (YEPI), it is possible to compare the level of national commitment to environmental protection (e.g., the 2018 US rank globally is 27th, Russia 52th, China 120th, UK 6th, and France 2th). Indeed, the 16 top YEPI countries are from Europe (31). Moreover, it is essential to incorporate the aggressive targets for reducing GHG emissions up to 2050, the countries' commitments, and the pressure against IOCs to comply.

Hence, the weight for LTO and YEPI should be more significant at the EU and water-stressed nations, given the perception differences relative to UHR development. Not surprisingly, Environmental Impacts (9.5%) and Core Technologies (9.1%) are the most influencing developing factors in China (23) and Poland (5). In the case of Argentina, where UOGD takes place in an area far away from towns, the factors and weights are Geology (20%), Commerciality (15%), Oil Field Service Capacity (15%), Financial Structure (10%), E&P Landscape (10%), Regulatory Landscape (10%), Infrastructure (10%) and Development Constraints (10%) (32). The Enabling Fiscal Regime factor will become more relevant shortly, echoing the rising requirements from equity and debt markets after the Covid-19 pandemic. Numerical results from Table 4 may not compare with previous works, as they are a compounded average useful for country ranking and competitiveness assessment after the proceeds from many countries. The results confirm this study's hypotheses, showing that those nations with difficulties to overcome the critical factors reflected in a UDI score below 4.0 cannot develop their UHR potential.

THE CASE OF COLOMBIA

Colombia has a significant potential for the seven types of UHR found. However, there is high volume uncertainty due to a lack of information (33). Declining conventional hydrocarbon exports are relevant for GDP and energy security and the main reasons to become another country pursuing UOGD. Incorporating the results and experiences from other nations reflected in the UDI allows us to evaluate and forecast the country's real possibilities to obtain UHR commercial development and adjust the critical factors.

The hydrocarbon production in Colombia has begun to decline since its 2015 peak due to a mix of lower oil and gas investment, less exploration, lack of relevant discoveries, and the maturity of the producing oil fields. The country enforced its UOGD regulation after ten years of global and local in-depth analysis. Consequently, some of the critical environmental, safety, and health risks can be avoided, and the remaining have a more reduced chance of occurrence. Some essential measures to be highlighted are:

(i) Flowback and produced water cannot be disposed of on surface streams.
(ii) It is mandatory to disclose chemicals used and to identify environmental health risks associated with their use.
(iii) For controlling induced seismicity, a maximum of 4.0 magnitude earthquakes is allowed before stopping operations.
(iv) Control and monitoring of air emissions, including methane, Vapour Oil Components, and flaring.
(v) Storage of waste fluids requires the use of tanks with ceilings to avoid air emissions.
(vi) Pits and ponds cannot be utilized for waste storage.
(vii) UOGD activities in environmentally sensitive areas or close to densely populated zones are forbidden. The planned operation should be performed in agricultural and cattle farming lands.

Since 2004, the country's appealing fiscal terms have attracted IOCs after the creation of the National Hydrocarbon Agency (ANH). ExxonMobil, ConocoPhillips, and Drummond have shown interest in UHR development in the country, and Tecpetrol, Chevron, Parex, and Gran Tierra could follow them. They can operate alone or in association with the NOC, Ecopetrol. The Olini, La Luna, and Tablazo shales in the Middle Magdalena Valley and Los Cuervos CBM and La Luna shale in Cesar Rancheria basins have spurred the most significant interest from IOCs and Ecopetrol. They are situated close to existing oil and gas infrastructure.

UDI score is 3.1, as shown in Table 4, reflecting a country placed in the Exploration category. After analyzing the current status, we identified the country's three (3) main factors (in red) to enhance and create appropriate conditions for successful UHR exploitation. Colombia must improve the grading from Conventional and Other Competition (3 to 5), Geology (3 to 5), and Public Opinion (3 to 5) factors to reach a score of 4.1.

A significant challenge faced by the industry today is the need to obtain the LTO. UOGD acceptance is needed, and communities will grant the LTO only if they trust that Ecopetrol and the IOCs operate in an environmentally, healthy, and safe manner. A window of opportunity is open after the execution of pilot tests defined by the government, following the recommendations from an expert commission entrusted with the study of UOGD risks and opportunities.

There are numerous uncertainties related to the UOGD, which is usual for a technology in its infancy, especially when it is new for a basin and more for a country. Colombia can leverage on the industry's operational learning curve, local updated and more rigorous regulations, industrial water reuse, and green technologies to overcome and even avoid the UHR exploitation difficulties in other countries. Moreover, given the awareness of environmental, health, and safety risks among stakeholders and IOCs' existence with strong cultural safety and sound operational practices involving occupational safety and process safety management, most of the ESG impacts would be controlled. The challenges lie in balancing the costs associated with risk mitigation and the risk tolerance level from the different parties involved. Additionally, to test the oil and gas potential and optimize the operations to reduce costs to allow financial and economic returns for the companies involved and the country.

CONCLUSIONS

Energy security is the main economic and strategic concern for those nations depleting conventional hydrocarbon production or importing energy supplies. However, there are substantial barriers that countries should overcome before commercial UHR exploitation is feasible. Nations like Russia, China, and Saudi Arabia, where NOCs address the challenge to exploit UHR on their own, lack the technology and knowledge required, despite having strong governmental support and capital availability. On the contrary, the way Argentina, Oman, and Turkey are attracting IOCs to work together with their NOCs allows them to emulate the North American results. At a lower scale, Eslovenia and Chile exploit UHR without IOCs by learning abroad and adapting local industry practices.

IOCs contribute capital, technology, and good practices to promote innovation via trial and error to generate the virtuous cycle required to obtain green production, operation optimization, and financial returns for UOGD. Governments can facilitate the process through UHR support, surface and subsurface risk reduction, fiscal regime improvement, and ESG practice promotion.

By proactively assessing, modeling, and addressing the critical factors required for UOGD utilizing the UDI, it is possible to foster developing UHR commercially. Researchers and policymakers can utilize UDI to evaluate the possibilities and requirements for any given country to exploit its UHR potential. With more countries working actively to exploit unconventional resources, it will be possible to update the Index to reflect new requirements, challenges and technologies and offer deeper insights regarding evolving critical factors for UHR exploitation.

Colombia is on the right path to attract the IOCs in alliance with its NOC, Ecopetrol. However, it requires testing UHR successfully and demonstrating that applying the best practices and technologies can exploit them economically and in an environmentally responsible manner for obtaining public support. The future of UHR development in Colombia will depend on a combination of different factors: the oil and gas industry demonstrating environmental and safe sustainable practice, confirmation of favorable resource potential, ability to obtain low-cost operation after complying with regulation and solve logistic challenges, and public support, with the latter being the most significant determinant.

Ecological sustainability and financial distress after Covid-19 are critical factors not evaluated herein, as their impact is still unknown. Their role around the world will be critical for UHR in the near future. Companies and countries able to successfully manage them will possess a distinctive competitive factor. Future studies should consider those aspects and update their results.

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NOMENCLATURE

ACA	Adaptive Conjoint Analysis
AHP	Analytic Hierarchy Process
Bb	Billion barrels
CD	Commercial Development
CO_2	Carbon dioxide
EIA	Energy Information Administration
ESG	Environmental, Social and Governance
EU	European Union
FID	Final Investment Decisions
GII	Global Innovation Index
LTO	Licensee to Operate
R&D	Research and Development
Tcf	Trillion cubic feet
TCM	Trillion cubic meters
UAE	United Arab Emirates
UD	Uncommercial Development
UDI	Unconventional Hydrocarbon Development Index
UHR	Unconventional Hydrocarbon Reservoirs
UOGD	Unconventional Oil and Gas Development
US	United States of America
YEPI	Yale Environmental Performance Index

APPENDIX

Definitions

Antifragile: an organization able to not only survive but also to prosper or thrive in turbulent environments.

Conventional and other competition: the presence or absence of rivalry from conventional hydrocarbon or other resources development.

Enabling Fiscal Regime: fiscal openness, stability, market liquidity, taxation, tax breaks, and other incentives directly influence the investor's return.

Geology: the quality of the rock, availability of data, easiness to fracture, and productivity.

Government Support: (i) energy security (local production versus energy imports); (ii) comparative costs of extracting unconventional versus importing hydrocarbons from foreign suppliers; (iii) the status of the economy; and (iv) degree of commitment of government officials to support UOGD.

Innovation: "the implementation of a new or significantly improved product (good or service), a new process, a new marketing method, or a new organizational method in business practices, workplace organization, or external relations" (33).

Land/access, Operability & Water Stress: the road and rail infrastructure, water availability after local needs, population density, land availability and land ownership, topography, customs, warehouses, and related aspects that impact operations.

Oil & Gas Infrastructure: service sector, pipeline, facilities, refineries, and other infrastructure that enables hydrocarbon exploitation, transportation, and commercialization.

Political environment: perceptions of government stability and the quality of public and civil services, policy formulation, and implementation (33).

Public Opinion (LTO): local community willing to accept operations.