



O&G 4.0: Leveraging Technology for Better Environmental Outcomes

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1 Introduction: The O&G Industry and its Climate Imperative

The flexibility, diverse applications, and high energy density of petroleum and hydrocarbons have rendered them the most marketable resource since 2000 (Cevik et al., 2020; Carson, 2023). The most widely consumed energy source globally is oil and gas (O&G). Price fluctuations of these resources, driven by shifts in supply and demand, play a critical role in the global economy (Kim & Perron, 2009) as primary energy sources for key industries such as transportation and electricity (Yang et al., 2023).

According to a recent report published by the International Energy Agency (2024), O&G continue to account for 55% of global primary energy demand. Far from diminishing their role in the energy demand matrix, some reports indicate that by 2050, fossil fuel sources are projected to constitute approximately 70% of the energy demand mix (Energy Information Administration, 2022). Certain studies warn that rising global population—and, consequently, increased energy demand—may stem from population growth in regions such as Asia and Africa. Geiger (2024) suggests that energy demand in non-OECD countries will increase through 2050, adding around 28 million barrels per day to global demand. Meanwhile, hydrocarbon demand is expected to decline in OECD countries due to intensified energy

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transition efforts. In contrast, hydrocarbon demand in countries like India is projected to grow by eight million barrels per day.

Although fossil fuels, including coal, currently account for approximately 80% of global energy production, estimates of remaining proven reserves vary significantly. It is important to distinguish between different fossil fuels, as their projected depletion timelines differ. For example, current proven coal reserves are estimated to last significantly longer than 47 years, while some estimates suggest oil and natural gas reserves could be depleted within that timeframe, assuming current consumption rates. It is crucial to note that these projections are subject to change based on factors such as future discoveries, technological advancements, and shifts in global energy demand. At the same time, the oil discovery rate has reached its lowest levels since 1950 (Mathur, 2023; Hayes, 2024).

Recent geopolitical events have also raised alarms regarding the dependence on fossil fuels. The ongoing war in Ukraine has posed a severe problem for Europe and its demand for Russian natural gas. This situation has led O&G companies to continue fossil fuel production under the premise of ensuring Europe's energy security, while also significantly reducing investments in green technology relative to previously set targets (Gordon, 2023). Aside from these decisions, driven primarily by geopolitical issues, technological advancements and green energy alternatives have increased in recent years. The O&G industry occupies a privileged position due to its extensive expertise in the energy market. Consequently, the industry faces pressure to direct technological investments toward reducing environmental impact and enabling the decarbonization of its activities. This is a crucial issue, as fossil fuels are still expected to play an essential role in meeting the rising global energy demand, despite popular opinion (Adomaitis, 2022; Litvin, 2023).

As expected, the O&G industry is under constant scrutiny from the market and society due to its questionable environmental and social practices, which in turn heightens pressure on these companies to take immediate action. Over the past year, CO₂ emissions from energy sources have increased by 1.3% (Fig. 1), reaching record levels and making it the hottest year since data collection began (International Energy Agency, 2024).

According to the World Energy Outlook 2023 published by the International Energy Agency, 15% of global energy-related emissions are attributable to O&G activities, amounting to 4.1 billion tons of CO₂ equivalent in 2022 (Levi-Johnson & Fitzsimmons, 2024). For example, in the United States, over 40% of energy production relies on natural gas, contributing roughly 8% of the country's greenhouse gas (GHG) emissions (Journal of Petroleum Technology, 2024) in the form of CO₂ and methane. A recent Stanford University study estimated methane emissions from the U.S. O&G industry at over 6 million tons per year, a figure three times higher than reported by the U.S. government (Myers, 2024). While CO₂ emissions remain the most widely used metric for assessing environmental performance, other factors, such as impacts on water, waste, soil, and biodiversity, are crucial in understanding the footprint of this industry. For instance, from 1964 to 2015, 514 oil spills from offshore pipelines were recorded, 20 of which involved volumes exceeding 1000 barrels (Stipes, 2023). The scientific community has documented numerous other

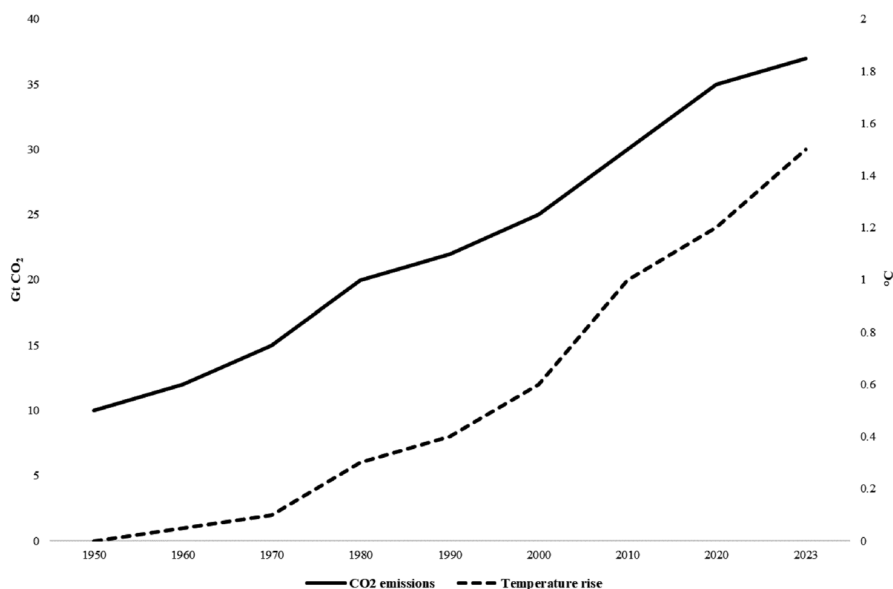


Fig. 1 Energy-related CO₂ emissions and temperature rise. Source: Own elaboration based on data extracted from International Energy Agency (2024). Notes: Gt CO₂ = gigatonne of carbon dioxide. Temperature rise above pre-industrial levels is the combined land and marine near surface annual temperature anomaly compared with the 1850–1900 level based on the average of HadCRUTS, Berkeley Earth, and National Oceanic and Atmospheric Administration data

environmental impacts caused by the O&G industry which are beyond the scope of this paper (Hayes, 2024). According to Koondhar et al. (2021), a higher consumption of renewable energy could contribute to a reduction in CO₂ emissions. Bilgili et al. (2016) also find similar results for 17 OECD countries.

Given the significant environmental and societal impacts mentioned, decarbonizing this industry has become central to the energy transition, alongside renewable energy investments (Hall & Morrison, 2024). Decarbonization is understood as the reduction of GHG emissions within an industry during its production process, as well as emissions generated by commercial end use by third parties. The International Energy Agency warns that the O&G industry, in particular, needs to cut emissions by 60% by 2030 to maintain global temperature increases within 1.5 °C (International Energy Agency, 2023a). According to that Agency, addressing unintentional methane leaks during O&G operations, which account for a third of global emissions, would drastically reduce the temperature rise resulting from greenhouse gases (Hansen, 2024).

O&G companies therefore play a crucial role in decarbonization efforts and the negative impact of production activities. As one of the key sectors at the international level, the O&G sector must play a key role in the socio-economic context. Through efficiency and technological innovation efforts, fossil fuels should drive the move toward alternative energy sources, which would also help align actions

with relevant international sustainability mandates such as the United Nations Sustainable Development Goals (SDG 7: Affordable and Clean Energy; SDG 13: Climate Action).

Both international oil companies (IOC) and independents consider a gradual energy transition feasible, allowing time for energy demand to be replaced by alternative sources. For now, these companies are focused on decarbonizing their operations and developing low-carbon alternatives, leveraging the logistics and infrastructure already established. A 2020 Ernst and Young analysis indicates that major integrated oil companies have reduced their upstream scope 1 and 2 emissions by approximately 20% since 2017 (Adomaitis, 2022). While substantial, these actions fall short of meeting established emission reduction goals.

In summary, the main objectives of this chapter are to learn about the current state of technology in the O&G sector and its application to decarbonization and the improvement of environmental performance; and, to map the different initiatives that private companies are currently undertaking at the international level. This will provide an overview of the different key technologies that will facilitate the energy transition of such an impactful sector.

2 Fueling the Future: Tech-Driven Transition

2.1 Energy Transition. An Unprecedented Challenge

The transition to renewable energy is crucial to achieve a more sustainable future (Imteyaz et al., 2021; Pilz et al., 2018). Despite efforts and investment directed toward renewable energy development over the past decade, fossil fuels remain the primary energy source for industrial activities and domestic consumption in modern economies (Swaray & Salisu, 2018). The rapid economic growth of the past century has created numerous environmental challenges, rendering the “high carbon, high development” model unsustainable amid fears of rapid climate change (Cong et al., 2022). A major warning comes from the Intergovernmental Panel on Climate Change (IPCC), which cautions that even in a low-emission scenario, global warming is likely or very likely to reach the established 1.5 °C threshold (IPCC, 2023).

According to the stance of certain leading institutions, achieving the energy transition appears to be formidable. The significant energy paradigm shift we are facing must contend with two distinctly opposing trends: on one hand, the need to decarbonize our economy to mitigate negative environmental impacts; and on the other, the ongoing need to meet rising energy demands with reliable, widespread, and durable energy sources (Jelinek & Kirsch, 2024). Beyond purely climatic data, other considerations include the necessary investment, the challenges of implementing these technologies, and the economic viability and commercialization hurdles of energy sources that have yet to be widely adopted, leaving questions of feasibility unanswered. According to a recent report by the International Energy Agency, the O&G industry would need to allocate 50% of its capital expenditure to clean technology projects to meet the 1.5 °C climate target. Given that only 2% of capital

expenditure was allocated to such projects in 2022, the goal is highly ambitious (Kimball, 2023). O&G companies are, in turn, at a crossroads: they must choose between continuing their core business for strong returns or responding to pressures urging the industry to invest in renewable energy, despite potentially uncertain profitability (Adomaitis, 2022). There is growing recognition of not only the importance of meeting future energy demand but also of how to meet this demand while minimizing negative impacts as much as possible (“3 Trends to Watch in the Oil and Gas Industry in 2024”, 2024).

Although renewable energy will play a crucial role in achieving decarbonization objectives, these goals may not be met without considering other decarbonization alternatives applied to conventional energy as well (Fossil CO₂ emissions at record high in, 2023, 2023).

2.2 The O&G Industry is under Pressure

“Companies around the world that rely on O&G and its by-products are under tremendous pressure to meet their decarbonization goals,” said Andrew Lefkowitz, CEO of Locus (Olivero, 2023). Global concern over the exponential rise in carbon emissions has made sustainability goals a priority for companies across many industries, especially in the O&G sector. To address these pressures and mitigate their impact, some companies are leveraging technological innovations in decarbonization to respond to stakeholders’ calls for change to meet sustainability targets (Levi-Johnson & Fitzsimmons, 2024). These pressures translate into the implementation of technologies that help reduce carbon emissions during core operations. Far from being an easy task, companies face a significant challenge, as these pressures require modifying much of the production and business practices they have been following. The implementation of these technologies must be efficient and financially viable, while also reducing the environmental impact (Pätäri et al., 2014).

Alternative investments need to be managed differently. Due to uncertainties regarding financial viability, companies must build a level of trust among their shareholders to make final investment decisions where all parties are aligned. In this way, an investment can be considered not only from a purely financial perspective but also in terms of its environmental performance (“Serious CCS trust deficits threaten net zero potential”, 2024). In this effort to balance both perspectives, technological innovation becomes an increasingly critical component, especially in the O&G industry. Innovation can enable companies to improve their environmental performance while maintaining stable financial viability, covering expenses, and making the project profitable.

Focusing strictly on the financial component, some O&G insiders caution that companies are currently not well-positioned to invest large sums of money in untested technologies research and development (R&D) efforts that may not be economically feasible. From the perspective of investors or lenders, such actions can presently appear as an excessively risky strategy compared to simply investing in fossil fuel exploitation and continuing business as usual (De la Garza, 2023).

According to a recent survey, 60% of surveyed O&G executives believe that low-carbon projects must achieve an internal rate of return (IRR) exceeding 12%–15% to be considered a good investment. In 2022, the IRR for many renewable projects was below 8%. The survey also highlighted concerns regarding scalability and market commercialization (Hardin et al., 2023). While technological innovation remains the best alternative for O&G firms to transform their production models, the financial viability of these projects must also align with shareholder and investor expectations. Currently, only 1% of global clean technology investments come from O&G companies (International Energy Agency, 2023b). One possible solution is the establishment of co-investments and long-term collaborations with innovative companies that already possess a strong technological foundation in decarbonization and renewable energy (De la Garza, 2023).

The strong financial performance of the O&G industry in recent years has led to increased expectations from investors, governments, and international institutions regarding the sector's role in the energy transition (Hardin & Mittal, 2023). This expectation translates into pressure on these companies to invest a portion of their profits in low-carbon technologies and demonstrate tangible progress in reducing emissions, even as they continue hydrocarbon exploitation. It remains to be seen whether this pressure will primarily result in investments focused on reducing the emissions associated with existing hydrocarbon operations or in diversification into entirely new clean energy ventures. Extracting these resources in an era of extreme global warming compels O&G operators to adopt new technologies and alternatives if they expect to maintain production levels in the region (Hardy, 2024). These efforts to mitigate the impact will shape the ongoing debate within the energy landscape regarding the “phased down” or “phased out” approach to fossil fuels.

2.3 Technology Innovation. The Best Ally of the O&G Sector?

To mitigate the aforementioned risks and impacts, green innovation within the O&G sector plays a crucial role (Aastvedt et al., 2021). Digital transformation can enhance the efficiency of O&G operations, particularly in terms of energy consumption and emissions. The specific objectives of implementing digital transformation within the O&G industry include: eliminating both intentional and unintentional gas leaks, electrifying rigs with low-emission sources, equipping current facilities with carbon capture, utilization, and storage (CCUS) technology, and expanding the use of bio-fuels and low-emissions hydrogen (International Energy Agency, 2023a). For instance, operations in the Permian Basin in the United States will soon require a greater number of electrification, digitalization, and automation projects to improve production efficiency and to meet increasingly stringent environmental regulations (Hardy, 2024). Another O&G hotspot, the North Sea, is making significant efforts in technological innovation to fulfill the industry's triple goal: supporting current O&G production, reducing emissions, and accelerating the shift toward a net-zero future (OGV Energy, 2024). Additionally, in the Middle East and North Africa

(MENA) region, the digital oilfield services market anticipates an investment increase up to \$41.73 billion between 2024 and 2029 (Čavčić, 2024).

Digitalization is expected to enable a reduction in emissions by up to 20% by 2050. Despite the high expectations for change, digital transformation is far from being free of challenges. Significant investment, rapid adoption and decision-making, and the integration of new technologies into already established processes are some of the key challenges the O&G sector must address (Levi-Johnson & Fitzsimmons, 2024).

The financial feasibility of this digital transformation may be one of the key pillars for making the energy transition scalable. According to ecological modernization theory, minimizing costs through the integration of new technologies could lead to a “win-win” situation from both environmental and economic standpoints (Lin et al., 2019). Authors such as Li (2014) and Lee and Min (2015) argue that green innovation can enhance both financial and environmental performance. Based on these findings, technological innovations could become the best allies for O&G companies, addressing pressures to reduce environmental impact while also yielding economic benefits from this shift. This shift is enabling optimization within the O&G sector by reducing costs, maintaining operational efficiency, and achieving sustainability goals (Schulz, 2024).

The International Energy Agency (2023c) projects that a significant portion of the 2050 energy mix could come from emerging technologies, including offshore wind, hydrogen, liquid biofuels, and carbon capture, utilization, and storage (CCUS). While these technologies hold potential, their large-scale deployment faces challenges. Hydrogen production costs remain high, the sustainability of some biofuels is debated, and CCUS requires substantial energy input. However, the pursuit of these and other decarbonization technologies is driving innovation within the O&G industry. This push toward greater operational efficiency and improved environmental performance is also leading to increased adoption of technologies like artificial intelligence (AI) and electrification (“Environmental sustainability: who are the leaders in natural gas CO₂ capturing?”, 2024). The following section analyzes the decarbonization technologies that have shown the most promise within the O&G sector to date (Fig. 2).

3 Top Innovations in the O&G Sector

In order to know which are the main technologies that the O&G sector is currently starting to implement for its decarbonization, a detailed analysis of each of them is made in this section. Along with each one, real examples that companies are currently carrying out are provided, being initiatives already in progress or projected for the future. As a result of this analysis, each of these initiatives is mapped to further clarify the efforts of the major companies and the locations where the greatest number of projects are being carried out.

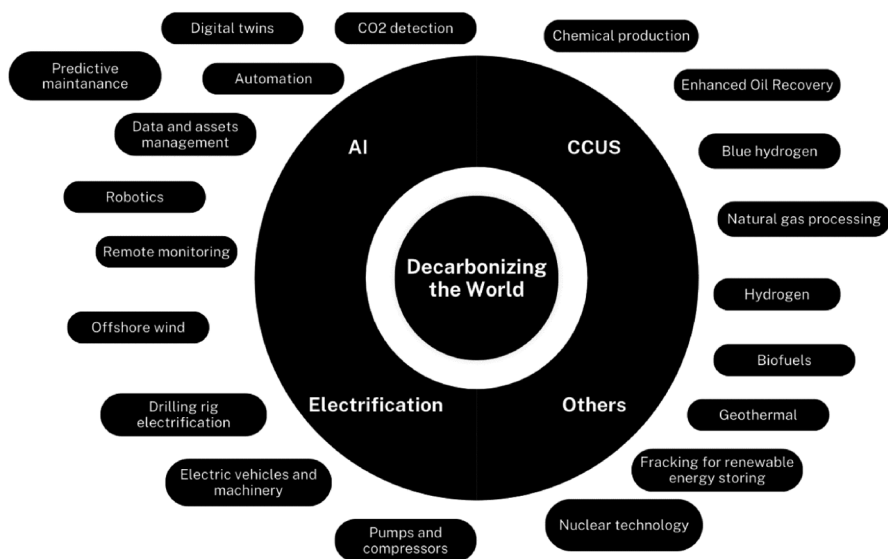


Fig. 2 Green Technology in the O&G Industry. Source: Own elaboration

3.1 Artificial Intelligence

AI has revolutionized the way companies conduct their production processes. In the O&G sector, the cost and timeline of exploration and exploitation activities have decreased considerably, making way for the implementation of new technologies that allow significant savings in time and resources. For instance, the implementation of digital twins (digital copies of an infrastructure) enables considerable resource savings in pipeline design. The O&G industry is increasingly using AI software that allows for early detection of oil spills and hydrocarbon leaks. With these systems, companies can quickly identify and assess the extent of the oil spill, providing a rapid response to mitigate potential environmental damage (Chirag., 2024). Beyond that, generative artificial intelligence (Gen AI) can generate maintenance plans, task lists, or real-time recommendations regarding a possible malfunction in production systems. This significantly reduces the time invested in problem detection and the resources employed for addressing such problems. Regarding the improvement in the industry's economic performance, Gen AI allows for real-time emissions monitoring, optimization of energy efficiency, reduction of waste, and even prediction of emissions throughout the supply chain (Hardin & Mittal, 2023).

According to a recent study, applications of AI in upstream activities that can contribute to a new understanding of this production process are: AI-based predictive maintenance, AI-powered digital twins, and IoT remote monitoring (Schulz, 2024). Between 2019 and 2023, investment in AI in O&G grew by 17% per year, and is expected to grow by 14% over the next decade. A survey conducted by EY

indicates that 92% of O&G companies globally are investing in AI or expect to do so in the next 2 years (Dubouski, 2024).

Aramco, the world's largest oil company, is making a significant investment in AI through the use of intelligent algorithms to analyze operational data, draw conclusions, and thereby improve processes and increase efficiency. One of its products, the i4Safety 2.0 Hazard & Incident Prediction, allows for the analysis of historical data to predict potential incidents and hazards in facilities, a tool that enhances safety for workers (Aramco, n.d.). Chevron also expects that quantum computing applied to the O&G market will increase by 37.9% in the coming years. The Texas-based company is investing large sums to develop its technology in quantum computing. These innovations could contribute to the discovery and development of new materials to achieve low-carbon products ("Chevron invests in quantum computing", 2024).

3.2 CCUS Technology

According to the International Energy Agency, it is estimated that capturing 32 billion tons of carbon dioxide is necessary to limit global warming to 1.5 °C. To achieve that goal, 26,000 terawatts of operational capacity are needed by 2050, which exceeds the global electricity demand in 2022. An investment of around \$3.5 trillion per year until 2050 is also required, an amount similar to the average revenues of the O&G industry in recent years (International Energy Agency, 2023a).

One of the innovations that might address this challenge is carbon capture, utilization, and storage (CCUS) (International Energy Agency, 2023c). CCUS allows for the capture and underground storage of carbon dioxide, thus preventing emissions from reaching the atmosphere. It is used to help carbon-intensive industries reduce their emissions, such as cement, steel, and petrochemical (Shell, n.d.). Not only is it possible to store carbon dioxide, but also to reuse it as a resource for other production processes ("U.S. should pursue CO₂ utilization", 2024). Some governments plan to invest heavily in CCUS in order to implement decarbonization strategies that allow them to reach their sustainability goals (Douglas, 2023).

The O&G sector is deeply involved in the implementation of this technology, precisely due to the high negative impact of the sector's activities. According to the International Energy Agency, 90% of global CO₂ capture and storage capacity is held by the O&G sector (International Energy Agency, 2023a). While it is true that CCUS technology is among the most promising for decarbonization, it is not without criticism. One challenge is the complexity of implementing this technology within existing facilities, which requires specific adaptations for a given area. Additionally, with different stages involved in the process—capture, transportation, storage, and use—it is common for each stage to be developed by a different company (Lebling et al., 2023).

CCUS has been available for some time, but it needs to become more efficient to be economically feasible. According to the International Energy Agency (2023d), approximately 75% of the projected carbon capture capacity for 2050 is currently

only in the demonstration or prototype phase of development. Out of the \$3 billion invested in CCUS in 2022, only 5% of the investments have reached the final stage of development (Russell, 2023). As of 2023, there were 42 operational CCS and CCUS projects worldwide, with a storage capacity of 49 million metric tons of CO₂ per year. This represents 0.13% of the 37 billion metric tons of energy-related CO₂ emissions annually (Douglas, 2023).

Despite the challenges, a survey of O&G executives indicates that 37% of respondents consider CCUS a critical aspect of their business strategy (Hardin et al., 2023). The O&G industry is increasingly recognizing the urgent need for CCUS within its operations to curb emissions and mitigate climate change. For instance, U.S. O&G companies are investing billions of dollars in CCUS and hydrogen technologies to reduce the climate impact of hydrocarbon fuels. According to some estimates, committed CCUS projects could reduce carbon emissions at a scale comparable to that achieved by the rapid adoption of electric vehicles (Jelinek & Kirsch, 2024).

Governments have invested around \$20 billion in CCUS to date, with over \$200 million already approved for future projects (“Carbon Capture’s Publicly Funded Failure”, 2023). Recently, the EU launched a strategic roadmap for CCUS, aiming to achieve a CO₂ capture capacity of 450 million tons by 2050 (“CCUS: Progressing Towards Bankability”, 2024). Japan considers CCUS a key component to reach its carbon neutrality target by 2050, with plans to develop sufficient CCUS capacity to store between 120 and 140 million tons of CO₂ per year by 2050 (Wood, 2023). In the USA, federal income tax credits have been incentivizing the launch of CCUS projects. The Inflation Reduction Act provides incentives of up to \$85 per metric ton of CO₂ stored (Watson, 2023).

Private initiatives are also taking root in the development and implementation of this technology. Occidental’s subsidiary, 1PointFive, is developing the South Texas Direct Air Capture (DAC) Hub. This project will have an initial removal capacity of 500,000 tonnes of CO₂ per year, with plans to expand to over one million tonnes annually. The site has the potential for further expansion, with a maximum capacity of up to 30 million tonnes of CO₂ removed per year (“Occidental’s 1PointFive South Texas DAC hub”, 2024). In the North Sea, Equinor, Shell, and TotalEnergies are advancing the Northern Lights project, which includes a receiving terminal, injection pipeline, and subsea infrastructure. This project is a part of Norway’s Longship initiative for carbon capture and storage, with targets to capture up to 1.5 million tons of CO₂ by 2024 and a total of five million tons by 2026 (“Northern Lights ready to receive CO₂”, 2024; Tveten, 2024). In Italy, Eni leads the Ravenna CCS project, the country’s first for permanent CO₂ capture, transport, and storage. The initial phase of the project is expected to store approximately 25,000 tons of CO₂ per year. The goal is to reduce CO₂ emissions by up to 90% from a natural gas processing plant that Eni operates in Ravenna. Additionally, the facilities will be fully powered by renewable energy sources to further minimize CO₂ emissions (Procyk, 2024).

However, it is crucial to contextualize these projects within the broader scale of global CO₂ emissions. While these initiatives represent important steps forward in developing and deploying CCUS technology, the captured amounts remain

relatively small. Global CO₂ emissions from fossil fuels alone are estimated to be nearly 40 billion tons annually. Therefore, even the combined projected capture capacity of these projects represents a minuscule fraction of the overall emissions challenge. Significant scaling up of CCUS deployment, along with other decarbonization strategies, will be essential to meaningfully address climate change.

3.3 Electrification

The electrification, digitalization, and automation of upstream present an opportunity for the O&G sector to significantly enhance production efficiency while reducing negative impacts and meeting climate targets (Hardy, 2024). For instance, a typical drilling rig requires between 6 and 50 MWh of energy per day. Using diesel to generate this energy poses a major issue due to CO₂ emissions, averaging about 20 metric tons of CO₂ equivalent per day. The emission intensity of a diesel-powered rig is 1 metric ton of CO₂ per MWh. Instead of relying on this system, highline electrical power can offer a viable alternative for rig electrification. The same rig powered by efficient generators and clean energy sources can emit around 0.39 metric tons of CO₂ per MWh (Landry et al., 2024). Currently, around 2% of the operational offshore wind capacity has been developed by O&G companies. Plans for renewable energy implementation in electrification are expected to grow, including new floating turbines that require substantial wind power in deep-water environments (International Energy Agency, 2023a).

Electrification offers the O&G industry a pathway to continue fossil fuel extraction while mitigating some of the environmental impact associated with supporting operations, such as the use of diesel generators. Replacing these systems with electric alternatives powered by renewable sources can reduce emissions, but the overall impact on the industry's carbon footprint depends on the scale of electrification and the source of the electricity. While electrification can contribute to operational efficiency and reduce certain emissions, it is important to note that it does not address emissions from the combustion of the extracted fossil fuels themselves, which represent the most significant contribution to the industry's overall environmental impact. This approach enables the industry to pursue a balance between energy security, affordability, and sustainability goals, albeit with continued reliance on fossil fuels ("3 Trends to Watch in the Oil and Gas Industry in 2024", 2024). As such, grid power has the potential to transform drilling practices worldwide.

Electrification is among the most promising means for reducing environmental impact, especially in intensive O&G operations like those in the Permian Basin (Hardy, 2024). British Petroleum (BP) has invested in electrical infrastructure throughout the Permian Basin. By the end of 2023, the company had electrified up to 95% of its wells in the area for drilling, pumping, gas compression, and control systems—activities traditionally reliant on natural gas or diesel. This shift has reduced the amount of methane emitted per unit of oil and gas produced by approximately 3% since 2019 ("BP electrifies 95% of Permian wells", 2024). Similarly, in the North Sea, TotalEnergies has launched a pilot project featuring a floating wind

turbine to supply electrical power to the Culzean offshore platform. The turbine is expected to be fully operational by the end of 2025, providing about 20% of the platform's required energy and thus replacing some power generation from gas turbines ("TotalEnergies launches offshore wind", 2024).

These examples highlight the growing trend of electrifying O&G operations, both onshore and offshore, to reduce reliance on fossil fuels for powering the operations themselves. Although the scale and impact of these initiatives vary, they demonstrate a shift toward cleaner energy sources for supporting processes within the industry. However, the key challenge remains decoupling overall emissions from production levels. While electrification can reduce the emissions associated with operational activities, it does not address the significantly larger emissions released during the end-use combustion of the extracted oil and gas. Therefore, a comprehensive decarbonization strategy must encompass not only operational improvements like electrification but also a transition toward lower-carbon energy sources in the broader economy.

3.4 Other Technologies

Hydrogen and Biofuels

O&G companies are also collaborating on large-scale projects for hydrogen production as an alternative fuel through systems like CCUS and electrolysis. In the International Energy Agency's Net Zero Emissions scenario, hydrogen use is expected to increase by a factor of 110 by 2030 (International Energy Agency, 2023a). Producing hydrogen and biofuels via electrolysis with renewable energy could enable O&G to generate decarbonized fuels for use in drilling equipment and transportation (Levi-Johnson & Fitzsimmons, 2024). The benefits extend beyond O&G operations: certain industries that rely on petroleum and gas derivatives could also leverage this innovation to reduce their environmental impact and achieve sustainability goals. For instance, ammonia—a gas currently used as fertilizer in industrial refrigeration, chemical production, and wastewater treatment—is highly polluting and is produced using natural gas. However, hydrogen from renewable energy sources and nitrogen from the air could also be combined to create a potential zero-emissions fuel for transportation and power plants (Verdonck, 2024).

Several O&G projects aim to produce hydrogen and other alternative biofuels. For instance, ADNOC and ExxonMobil have reached an agreement to develop a low-carbon hydrogen and ammonia production plant in Baytown, Texas. According to the operators, this facility is projected to be the world's largest of its kind, capable of converting natural gas into hydrogen while reducing CO₂ emissions by up to 98%. The plant is also expected to generate over 1 million tons per year of low-carbon ammonia (Adams, 2024). Another noteworthy project is by Compañía Española de Petróleos SAU (Cepsa) in Port Huelva in Palos de la Frontera, Spain. Cepsa, in a joint venture with Apical Group (Singapore), is developing a new renewable fuels plant aimed at producing up to 500,000 tons per year of renewable diesel

and sustainable aviation fuel from a feedstock of agricultural waste and used cooking oils (Brelsford, 2024).

Geothermal

Geothermal energy shares many similarities with upstream operations, particularly in developing new technologies that can support the decarbonization of carbon-intensive activities (International Energy Agency, 2023a). Geothermal energy (energy extracted from the heat given off by the soil and subsoil) is a reliable source that provides a constant flow of power, making it suitable for a wide range of industrial processes. Currently, geothermal energy accounts for about 1.6% of the U.S. energy mix (De la Garza, 2023). According to the Department of Energy, there may be enough geothermal energy in the USA to power 65 million homes by 2050 (Office of Energy Efficiency & Renewable Energy, 2023). This growth potential is appealing to O&G companies that aim to become major players in geothermal energy development. This form of energy shares operational similarities with current fossil fuel practices, thereby having the potential to reduce costs as well as implementation and scalability risks. These similarities suggest that the drilling methods behind the 2010 shale oil boom may also be essential for expanding geothermal energy deployment (De la Garza, 2023).

Although geothermal energy as a decarbonization tool for O&G is a relatively recent development, some companies are beginning to test and invest significant sums in exploring pathways to make geothermal a viable alternative for industry decarbonization. In northern Nevada, Fervo Energy recently announced the successful initial testing of its next-gen geothermal plant, through which it aims to decarbonize its operations (De la Garza, 2023). Additionally, O&G giant Chevron has joined the movement, investing \$25 million in Swedish geothermal developer Baseload (Richter, 2021). Other major players like OMV and BP are investing in geothermal, such as Canadian geothermal startup Eavor Technologies (Eavor, 2023).

Additional Technological Applications

Although this chapter has focused primarily on more established decarbonization efforts within the O&G sector, we conclude by highlighting some of the more innovative, not widely known, it seemed fitting to highlight in this chapter some of the most innovative initiatives, albeit often less publicized initiatives. Many of these represent ambitious, early-stage investments that, while not currently commercially viable, hold promise for future breakthroughs as a result of ongoing research and development.

One example involves several U.S. startups that are developing hydraulic fracturing (fracking) technologies to store renewable solar and wind energy in underground pressurized water reservoirs. This initiative focuses particularly on decarbonizing high O&G-intensive regions like the Permian Basin. The new pressurized storage technology could become a highly feasible alternative to lithium batteries, provided that various tests confirm its viability and scalability. This infrastructure is expected to enable long-term energy storage, potentially eliminating the intermittency and inconsistency that currently characterize renewable energy sources. The fracking

process used to implement this technology is anticipated to be less environmentally damaging than its traditional application in O&G operations (Paraskova, 2024).

Viaro Energy and Newcleo recently signed a Memorandum of Understanding (MoU) focused on decarbonizing O&G infrastructure through the use of nuclear energy. This initiative centers on the development of advanced modular reactors (Čavčić, 2024).

Finally, abandoned oil and gas wells may potentially be repurposed for carbon and hydrogen storage. Wells which are no longer in use and are decommissioned pose a significant environmental hazard due to methane leaks. Aquaterra Energy aims to address this issue by developing technologies that not only manage the sealing of these wells but also give them a second life as a solution for carbon and hydrogen storage (“Aquaterra Energy launches legacy well re-entry”, 2024).

4 Key Findings and Discussion

After the analysis of scientific papers, news, and industry reports, we have tried to make a detailed summary of the main initiatives that the O&G sector is currently carrying out to decarbonize its activity. It turns out that AI and CCUS are currently the technologies that are being implemented the most in the sector, mainly due to the capabilities that companies have to innovate and adapt these technologies to the traditional activity of extraction, refining, and transportation of oil and gas. Also, electrification is another of the technologies that is currently being implemented the most. Using renewable energies to serve as an energy source on oil platforms, for example, is becoming a relatively viable technology for economic purposes, thus allowing the company’s own emissions during its activity to be considerably reduced. It has also been observed that there are other technologies, although still in a nascent state, that are very promising for the decarbonization of the sector. Solutions such as hydrogen, geothermal energy, or biofuels are promising components of this mix of technologies that will help the sector to decarbonize in the coming decades in order to meet the proposed international emissions targets.

Figure 3 maps some of the most relevant projects discussed throughout this section. The main technologies discussed in this chapter have been taken into account for the creation of the map. It should be noted that the selection of these technologies is due to the importance and relevance that the media and official websites of the main companies give to these types of alternatives as the most efficient tools for improving environmental performance and achieving the sustainable objectives that accompany the energy transition. The location, the type of technology, and the main companies carrying out the projects have been highlighted on the map. Some of the most relevant projects have been highlighted in more detail in previous sections.

It is noteworthy to highlight the geographic concentration of decarbonization projects in the O&G sector, primarily focused in the U.S. and the North Sea region, both areas with high O&G activity. Canada, Argentina, Malaysia, and Australia also have decarbonization projects that are in development or already operational.

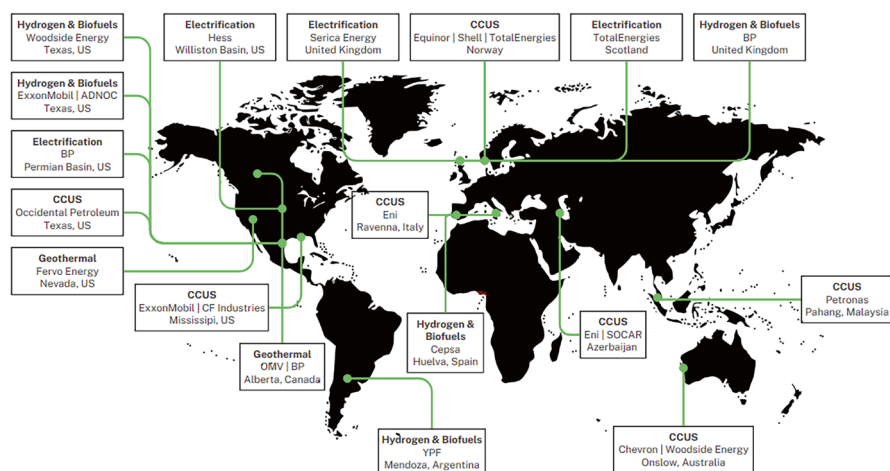


Fig. 3 Mapping decarbonization in the O&G sector. Source: Own elaboration

In recent decades, the O&G has been characterized as one of the sectors with the greatest environmental impact, ranking among the largest emitters of CO₂ into the atmosphere (Levi-Johnson & Fitzsimmons, 2024). Numerous scientists have empirically confirmed the significant environmental impacts of the O&G sector, not only in terms of emissions but also concerning oil spills, waste management, and water usage (Hayes, 2024).

Given this impact—and as the primary motivation for drafting this chapter—the decarbonization of the sector has become a crucial element in achieving the sustainability goals set by international organizations for 2030 and 2050 (Hall & Morrison, 2024). The adoption of new technologies and the implementation of initiatives aimed at reducing the sector's impact could result in improved environmental performance (García-Amate et al., 2023). Additionally, the pressure these companies are facing from governments and the market (Levi-Johnson & Fitzsimmons, 2024) to begin decarbonizing their operations may explain the current surge in innovation initiatives.

As observed in the analysis, the authors warn that innovation must not only reduce environmental impact but also be financially viable (Pätäri et al., 2014; Hardin et al., 2023). Previous studies, such as those by Ramírez-Orellana et al. (2023), have demonstrated that implementing technologies to improve the O&G sector's environmental performance can lead to increased financial profitability and reduced market risk. These findings may explain the large number of initiatives identified in this chapter.

It is possible that companies are beginning to find a balance where implementing new decarbonization technologies becomes economically profitable, thereby achieving not only environmental sustainability goals but also operational, cost-related, and market valuation improvements due to stakeholder pressures. Authors such as Li (2014) and Lee and Min (2015) argue that green innovation can enhance

both financial and environmental performance. Based on these findings, technological innovations could become the O&G sector's best allies, addressing pressures to reduce environmental impact while delivering economic benefits from this transformation.

5 Conclusions

For centuries, the economic system has been powered by the large-scale development and use of fossil fuels. Despite significant efforts to transition to cleaner energy, major organizations continue to warn that much more needs to be done to meet climate targets. Today, fossil fuels remain the most widely used energy source globally, especially in rapidly growing countries like India and China. This challenge is compounded by the projected population growth in these areas and the need for reliable, consistent energy to meet that demand. To date, no energy source has matched fossil fuels' flexibility, energy density, and applicability across critical sectors such as industry, transportation, and petrochemicals.

The O&G industry ranks among the highest in CO₂ emissions, water usage, waste production, and energy inefficiency. As a result, O&G companies have increasingly come under scrutiny from investors, shareholders, and major institutions. Given the O&G industry's long-standing focus on fossil fuel extraction, refining, and commercialization, a complete and immediate overhaul of its operations appears unlikely. This inherent inertia fuels an intense debate: should society prioritize a rapid cessation of fossil fuel consumption, or pursue a more gradual reduction coupled with aggressive decarbonization efforts? This fundamental tension between immediate cessation and mitigated continuation defines the core challenge facing the industry and society today.

It is not only international institutions calling for imminent change: the market itself, along with shareholders and investors, is beginning to align with climate goals to keep global warming within 1.5 °C. This pressure, along with the need for change, appears to have led the O&G industry to begin focusing more seriously on adopting and developing new technologies to decarbonize their operations.

Contrary to the general public's perception, the O&G industry is investing substantial economic and financial resources in efforts to reduce the negative impact of its activities. Leveraging their extensive engineering capabilities and decades of experience in developing new technologies, companies are beginning to apply their expertise to technologies that could lead to improved environmental performance—an outcome society and critics of the industry are increasingly demanding. AI is enhancing efficiency in production activities, reducing resource use, time, and environmental impact. The development of digital twins, for example, enables the creation of infrastructure simulations through quantum computing, avoiding the physical development of structures and mitigating future risks. Other applications, such as early detection of potential oil spills via big data management or emissions monitoring on a rig, can be critical in reducing industry's negative impact. Among the most promising technologies in the O&G sector are CCUS technology,

electrification, and the production of hydrogen and biofuels. These avenues are considered fundamental pillars in O&G's path toward effective and lasting decarbonization.

6 Future Outlook

However, despite the industry's significant efforts to decarbonize its operations, achieving climate goals remains distant as we approach 2030 and 2050 deadlines. Developing new technologies and implementing and scaling them is a multi-year endeavor. The financial viability and commercialization of these technological solutions are also critical considerations that non-governmental institutions and governments must recognize and support companies for whom implementing technological innovations may not be financially viable. Also, as part of the O&G supply chain, consumers also play a crucial role in the decarbonization of the sector. The increase in the consumption of renewable energy, or the recent implementation of electric vehicles on the road, can lead to a reduction in fossil fuel consumption, which can also reduce the negative impact of the sector and thus put pressure on companies to change their business model to a more sustainable one. But, without a financial return, shareholders and investors are unlikely to support continued investments, which would significantly slow the adoption of decarbonizing technologies and prolong the negative consequences of fossil fuel production and consumption. Decarbonization is a crucial goal. However, overly optimistic projections, even from reputable institutions, risk diverting resources from potentially more effective strategies and obscuring the true scale of the challenge. This potential misallocation of resources could have significant long-term consequences, hindering the effective and timely transition to a sustainable energy future.

To avoid these consequences, research in this field should focus on two fundamental ways: improving the technological development of these initiatives to reduce the cost of implementation and thus increase the number of companies that decarbonize their activity by introducing these technologies. On the other hand, the implementation of international policies that help the practical implementation of these technologies in the daily activity of the O&G is certainly very necessary. Further research on this point will allow conclusions to be drawn that will help to identify possible areas on which to focus efforts to encourage and finance these initiatives.

Apart from the implications of the study, it is not without its limitations. The analysis itself is a theoretical study with a macro and prospective analysis of the situation of the industry with respect to technological innovation and its impact on the improvement of sustainability. Thus, the study does not denote a statistical character, which may reduce the extraction of empirical results to inform possible future decisions. Robust statistical analysis and analysis of the relationship between technological implementation and environmental performance could alleviate these limitations in the future.

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