

Integrating Industry 4.0 and 5.0 technologies for sustainable, resilient oil and gas production operations

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Abstract. In response to escalating environmental concerns, fluctuating markets, and swift technological advancement, the oil and gas industry is increasingly challenged to improve operational resilience while pursuing sustainability. Meeting these concurrent demands requires forward-thinking strategies that embrace cleaner technologies, enhance resource efficiency, and strengthen adaptability to external pressures, without compromising profitability or regulatory obligations. By employing qualitative content analysis and triangulation techniques, this study investigates 20 leading oil and gas firms to examine how the implementation of Industry 4.0 and 5.0 technologies is reshaping their approaches to resilience and sustainable operations. Industry 4.0 is characterized by advanced data analytics, artificial intelligence (AI), and the Internet of Things (IoT), while Industry 5.0 emphasizes human-machine collaboration and environmental stewardship. This study demonstrates that integrating these technologies enhances operational efficiency, reduces environmental impact, and improves safety within the industry, thereby supporting the objectives of key sections of the United Nations (UN) Sustainable Development Goals (SDGs) 7, 8, 9, 12, and 13. Organizations that adopt these innovations are better prepared to manage market fluctuations and regulatory pressures, which promotes sustainability. However, they face challenges such as high implementation costs, skill gaps, cybersecurity threats, and regulatory complexities. Notably, these challenges exist in both global and developing contexts, with variations primarily in their scale, access to resources, institutional support, and overall preparedness. The research underscores the importance of workforce upskilling, flexible strategies, and partnerships with technology providers for successful digital transformation. Additionally, it provides a strategic framework to guide oil and gas companies through this process.

Keywords: human-machine collaboration, industry 4.0 and 5.0 technologies, oil and gas industry, resilience, sustainability.

1. Introduction

The oil and gas industry remains a cornerstone of the global energy landscape, underpinning economic growth and sustaining contemporary lifestyles. Despite its critical role, the sector faces significant challenges, including volatile market demands, geopolitical uncertainties, strict environmental regulations, and operational risks associated with remote and extreme conditions [1]. Increasing global emphasis on sustainability and environmental responsibility has intensified the need for the industry to enhance operational resilience while implementing sustainable practices. Addressing these multifaceted challenges necessitates a transformative approach that integrates advanced technologies to improve efficiency, safety, and sustainability.

The emergence of Industry 4.0, commonly referred to as the Fourth Industrial Revolution, has revolutionized traditional operational practices through automation, data exchange, and interconnected systems [2]. Characterized by the integration of advanced data analytics, AI,

robotics, and the Internet of Things (IoT), Industry 4.0 enables firms to optimize resource utilization, improve decision-making, and reduce operational costs [3]. IoT-enabled sensors, for instance, generate real-time data, enhancing responsiveness and agility in managing complex supply chains. Building upon this, Industry 5.0 introduces a paradigm shift by emphasizing human-machine collaboration, human-centric values, and environmental sustainability. Together, they represent a shift from purely digital efficiency toward sustainable, human-centered innovation [4], [5]. This emerging framework provides an opportunity for the oil and gas sector to address pressing operational challenges by leveraging advanced technologies alongside human expertise while aligning with global sustainability goals.

Despite the transformative potential of Industry 4.0 and 5.0, current research in the oil and gas sector predominantly focuses on automation, robotics, and AI-driven processes, often neglecting the critical role of human-machine collaboration [6]. There is a pressing need for studies that explore how human decision-making, adaptability, and expertise can be effectively integrated with technological innovations to enhance safety, efficiency, and problem-solving. Additionally, although Industry 5.0 highlights sustainability and resilience, limited research has investigated how these principles apply specifically within the oil and gas context. There is a clear need to evaluate how technology adoption can improve energy efficiency, reduce carbon emissions, and enhance asset reliability, while fostering operations resilient to market fluctuations, equipment failures, and regulatory changes.

Another notable gap in the literature concerns digital transformation and workforce adaptation. As digital technologies reshape industry operations, it is essential to examine their impacts on workforce roles, skill requirements, and overall performance. Understanding how Industry 4.0 and 5.0 technologies influence productivity, job design, and employee competencies is crucial to ensuring workforce readiness and sustainable industry growth.

In response to these challenges, this study explores the integration of Industry 4.0 and 5.0 technologies within the oil and gas sector, focusing on enhancing operational resilience and sustainability. By examining the interaction between advanced technologies and human-centered approaches, the research aims to provide a comprehensive understanding of how these combined efforts can improve operational efficiency, reduce environmental impact, and optimize resource utilization. The study analyzes real-world applications from 20 global oil and gas companies, highlighting practical benefits and contributions toward achieving the United Nations Sustainable Development Goals (SDGs).

The study employs a qualitative content analysis approach with triangulation, systematically reviewing company websites, sustainability reports, and case studies to extract insights on technology adoption and its impact on operational efficiency. Findings are cross-validated with scholarly literature, industry reports, and the SDGs to ensure reliability and contextual relevance. By identifying key technological applications and their outcomes, the research provides valuable guidance for industry stakeholders seeking to enhance resilience, sustainability, and efficiency in a rapidly evolving energy landscape.

The significance of this study extends beyond addressing research gaps. It offers actionable insights for policymakers, industry leaders, and other stakeholders on integrating advanced technologies to promote operational resilience and environmental sustainability. The findings inform strategies for transitioning toward a sustainable energy future, support regulatory and corporate decision-making, and provide broader implications for global sustainability and climate change initiatives. By showcasing best practices and successful case studies, the study contributes to the development of innovative, technology-driven business models emphasizing resource efficiency, environmental stewardship, and resilient operations across multiple sectors.

1.1. Research aim

This study aims to assess how the integration of Industry 4.0 and 5.0 technologies enhances operational resilience and sustainability in the oil and gas sector. It seeks to offer insights into the

transformative effects of these technologies, their practical applications, and strategies for utilizing them to tackle industry challenges, including environmental issues, market volatility, and resource optimization.

1.2. Research focus: objectives, questions, and gaps

Table 1 outlines the core focus of the research by detailing specific objectives, guiding questions, and identified research gaps. It provides a structured overview that connects the study’s purpose, inquiry direction, and areas requiring further investigation or improvement.

Table 1. Research objectives, research questions, and research gaps

S/No.	Research objectives	Research questions	Research gaps
1.	To analyze the impact of Industry 4.0 and 5.0 technologies on resilience and sustainability in the oil and gas sector	How do Industry 4.0 and 5.0 technologies enhance operational resilience and sustainability in the oil and gas sector?	Limited exploration of human-machine collaboration in Industry 4.0 and 5.0 within the oil and gas sector
2.	To critically examine the key benefits and challenges encountered by global oil and gas companies in the implementation of Industry 4.0 and 5.0 technologies	What are the key benefits and challenges faced by global oil and gas companies in implementing Industry 4.0 and 5.0 technologies?	Insufficient analysis of sustainability and resilience strategies in Industry 5.0 for the oil and gas industry
3.	To develop a strategic framework for the adoption of Industry 4.0 and 5.0 technologies in the oil and gas sector	What strategic framework can be designed to facilitate the adoption of Industry 4.0 and 5.0 technologies in the oil and gas sector?	Lack of comprehensive studies on the impact of digital transformation on workforce roles and operational performance

1.3. Literature review

Industry 4.0, representing the Fourth Industrial Revolution, introduced automation, IoT, AI, robotics, and advanced analytics to improve efficiency and resource management, enabling innovations such as digital twins, predictive maintenance, and highly interconnected systems. Building on this progress, Industry 5.0 prioritizes human-machine collaboration, sustainability, and resilience by integrating human judgment with intelligent technologies to support environmentally responsible operations. Together, these frameworks shift industry focus from digital optimization to sustainable, human-centered innovation. Their application in the oil and gas sector is increasingly viewed as essential for enhancing resilience, sustainability, and operational efficiency as the industry adapts to rising energy and environmental demands [7].

Existing research underscores both the opportunities and complexities of this digital transformation. For instance, [8] examined the influence of Industry 4.0 on the digitalization of oil and gas operations, reporting significant gains in operational efficiency. However, they also stressed the importance of moving beyond purely technical perspectives by incorporating social dimensions through the Industry 5.0 framework. This perspective emphasizes the role of cyber-physical-social systems (CPSS) in creating a more human-centered industry model. In line with this shift, [9] introduced the concept of Operator 4.0, highlighting how wearable technologies can safeguard workers in high-risk environments. Extending the discussion further, [10] demonstrated how collaborative robots and cognitive digital twins are reshaping industry practices, enabling operations to become more adaptive, intelligent, and sustainable.

Despite these promising advances, scholars caution that several barriers continue to hinder widespread adoption. [11] identified persistent obstacles such as technical complexity, cybersecurity vulnerabilities, organizational inertia, and the absence of fully deployable technologies. Through Interpretive Structural Modeling (ISM), their study offered strategic

pathways to strengthen digital adoption and optimize resource utilization. Complementing this, [12] conducted a systematic review of 223 publications spanning nearly a decade, identifying AI and the IoT as vital for upstream operations. Yet, their findings also pointed to the underutilization of transformative tools like additive manufacturing and virtual reality, particularly in light of market volatility and global decarbonization pressures.

Other scholars have approached the digital transformation challenge from a practical implementation standpoint. For example, [13] proposed an intelligent retrofitting model that combines the IIoT with the Digital Triplet (D3) framework, thereby enhancing system resilience while strengthening human-machine collaboration. Their work illustrates the growing role of artificial intelligence, machine learning, and augmented reality in bridging operators with cutting-edge technologies. Similarly, [14] emphasized that achieving operational excellence and long-term sustainability requires a strong focus on predictive maintenance, proactive risk identification, and safety instrumented systems (SIS), all of which reduce hazards while boosting performance.

Taken together, the literature provides compelling evidence that Industry 4.0 and 5.0 technologies are critical to optimizing efficiency, resilience, and sustainability in the oil and gas sector. However, challenges such as high adoption costs, workforce skills gaps, cybersecurity threats, and regulatory hurdles remain significant barriers. What emerges clearly from these studies is a consensus: the future of oil and gas lies in adopting human-centered, technology-driven strategies that harmonize advanced digital tools with operational realities to achieve a sustainable and resilient transformation.

2. Methodology

The study employed a qualitative content analysis method, complemented by triangulation techniques. Content analysis is a structured, objective, and reproducible research approach used to examine and interpret the content of textual, visual, or audio data [15]. It enables researchers to detect patterns, themes, frequencies, and underlying meanings within communication materials [16]. This method is widely applied across various fields, including the social sciences, media studies, psychology, and education.

Fig. 1 presents the methodological flow chart outlining the structured approach adopted in this study. The process integrates qualitative content analysis with triangulation techniques, ensuring a comprehensive and multi-perspective examination. The final phase involved a detailed discussion and analysis of outcomes, aimed at enhancing the rigor, reliability, and contextual richness of the findings. A breakdown of each stage is provided below.

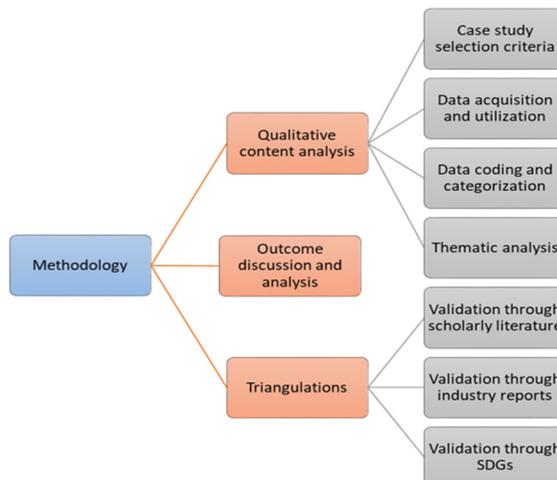


Fig. 1. Methodological flow chart

2.1. Qualitative content analysis

The method involved a structured process of data collection, coding, and thematic analysis to uncover recurring patterns, relationships, and insights across multiple qualitative data sources. By analyzing textual data from company reports, case studies, and academic literature, the study was able to provide a detailed understanding of how digital transformation efforts contribute to enhancing sustainability and operational resilience within the industry.

2.1.1. Case study selection criteria

Twenty prominent oil and gas companies were selected for case analysis based on three major criteria: geographical representation, technological advancement, and operational scale. Companies were chosen from diverse regions to capture a wide range of environmental, regulatory, and market conditions. Firms known for leading in digital transformation, those actively investing in AI, IoT, automation, and sustainability technologies, were prioritized to ensure the relevance and richness of the case studies. Also, the selection focused on companies with significant operational scale, including upstream, midstream, and downstream activities. This ensured that the study covered a broad spectrum of organizational practices and offered generalizable insights into the global application of Industry 4.0 and 5.0 technologies. Table 2 presents the classification of companies based on their geographic coverage, technological sophistication, and operational scale.

Table 2. Categorization of companies according to their geographical reach, technological capabilities, and scale of operations

Company	Geographical representation	Advancements in technology adoption	Operational scale	Application
BP	Global presence, headquartered in the UK	Advanced in energy transition technologies and digitalization	Large-scale, major operations in upstream, midstream, and downstream	Large-scale, major operations in upstream, midstream, and downstream
TotalEnergies	Global, strong presence in Europe and Africa	Invests in renewable energy, carbon capture, and digital technology	Significant operations across all sectors	Focused on transitioning to a low-carbon future while maintaining scale
Saudi Aramco	Primarily in Saudi Arabia, a global presence	Cutting-edge in oil extraction and digital tech	World's largest integrated oil company	Strong focus on sustainability and LNG technology
Woodside Energy	Australia, expanding internationally	Investments in LNG technologies and energy efficiency	Focused on LNG and deepwater oil operations	Strong focus on sustainability and LNG technology
TechnipFMC	Europe, North America, the Middle East and Asia Pacific	Leading in subsea processing, digitalization, and integrated technologies	Large-scale operations across offshore, subsea, and subsea systems	Forefront of subsea innovation, with significant advancements in underwater processing, AI, and automation
Gazprom	Primarily in Russia, which has large global exports	Focus on gas technology, pipelines, and energy distribution	Major gas producer, with large-scale pipeline systems	Technologically focused on natural gas infrastructure and distribution
Marathon Oil	Primarily in the U.S., global presence	Advanced in oil exploration and drilling technologies	Focus on upstream oil and gas, with global presence	Strong in shale and deepwater oil fields

Baker Hughes	Global, based in the U.S.	Industry leader in oilfield services, digital solutions	Global services and technologies for the oil and gas industry	Leading in oilfield services, automation, and AI solutions
Halliburton	Global presence, based in the U.S.	Strong in well services, digital technologies, and AI-driven solutions	Wide-reaching services across upstream and downstream	Prominent in digital technology for drilling and completion services
Schlumberger	Global, headquartered in the U.S.	Advanced in automation, digital tools, and sustainable tech	Large scale, serving the full oil and gas value chain	Leader in digital transformation within oilfield services
Adnoc	Based in the UAE, strong Middle East presence	Investments in AI, digital tools, and carbon capture	Large scale in upstream, midstream, and downstream operations	Focus on digital transformation, sustainability, and efficiency
OMV's ReOil	Austria, with European and global projects	Focused on recycling CO ₂ , renewable energy, and digitalization	Primarily upstream and sustainability-driven	Leading in carbon-neutral and renewable energy initiatives
Enbridge	Primarily in North America, with global reach.	Invests in pipeline infrastructure and renewable energy tech.	Major pipeline and midstream operations.	Key player in North American energy infrastructure and clean energy.
ConocoPhillips	Global, with a significant presence in North America	Advanced exploration technologies, carbon management	Large-scale upstream operations worldwide	Strong technological investments in exploration and sustainability
Repsol	Spain, with global operations	Leader in renewable energy and energy transition technologies	Integrated oil and gas operations, major in renewable transitions	Transitioning to renewable energy with major tech investments
Eni	Italy, has a significant presence in Africa	Focused on sustainable energy and decarbonization technologies	Large-scale, with operations in oil, gas, and renewables	Strong in transitioning to cleaner energy sources
Chevron	Global, with a major presence in the U.S.	Advances in digital technologies, automation, and clean energy initiatives	One of the largest integrated oil and gas companies	Investments in sustainability while maintaining significant scale
Equinor	Primarily Norway, global presence	Leader in offshore and wind energy, carbon capture	Strong in offshore oil and gas and renewable energy	Focused on sustainability and transitioning to renewables
ExxonMobil	Global, with a major presence in the U.S.	Focus on AI, automation, and carbon capture technologies	One of the world's largest integrated oil companies	Leading in technological adoption for operational efficiency
Shell	Global, headquartered in the Netherlands	Leader in energy transition technologies, and carbon capture	Major operations in oil, gas, and renewables.	Transitioning to low-carbon technologies and renewables, focusing on sustainability

2.1.2. Data acquisition and utilization

Based on the studies by [17] and [18], which highlight the role of data analytics in enhancing decision-making, strategic planning, and efficiency, this study adopted a structured approach to data acquisition. Three primary sources were utilized: company websites, sustainability and

annual reports, and technological case studies. Company websites were examined to identify digital transformation initiatives, sustainability programs, and strategic directions reflecting technological priorities. Sustainability and annual reports provided insights into environmental performance, safety standards, and technology-driven advancements aligned with global sustainability goals. Real-world case studies were also analyzed to assess the practical application of advanced technologies, operational outcomes, and implementation challenges. Additionally, operational reports, academic research, industry publications, and proprietary databases offered supporting evidence on technology adoption levels, performance metrics, and financial indicators.

2.1.3. Data coding and categorization

After data collection, a systematic coding procedure was undertaken to derive meaningful insights from the textual data. Both open and axial coding techniques were utilized: open coding helped identify recurring words, ideas, and expressions, while axial coding grouped these into higher-level categories. The key categories that emerged included digital transformation, human-machine collaboration, sustainability alignment, and resilience enhancement. The entire process was facilitated through NVivo. To ensure reliability, the coding was conducted iteratively and supplemented with manual cross-verification. This systematic approach converted raw qualitative data into well-structured analytical information, laying a solid groundwork for the subsequent thematic analysis.

2.1.4. Thematic analysis

Coded categories were synthesized into overarching themes that represented the core dimensions of Industry 4.0 and 5.0 adoption in oil and gas operations. Five dominant themes emerged; resilience, sustainability, adoption benefits, technology involved and implementation challenges, which shaped the organization of the results presented in Sections 3.1 to 3.4. This thematic development provided a coherent structure for interpreting the findings, linking company-level initiatives to broader industrial and sustainability implications.

2.2. Triangulations

Validation in this study was achieved through multiple sources: scholarly literature offered theoretical grounding; industrial reports provided practical insights and empirical relevance; and benchmarking against the UN SDGs ensured alignment with globally recognized standards for sustainability, resilience, and industrial transformation.

2.2.1. Validation through scholarly literature

To enhance the credibility of the analysis, the identified themes were cross-validated against established academic frameworks and theoretical models. Peer-reviewed studies on digital transformation, sustainability engineering, organizational resiliency and Industry 4.0 and 5.0 particular to the oil and gas operations were reviewed to ensure that interpretations aligned with recognized conceptual models. This validation process confirmed that the relationships uncovered through coding were both theoretically sound and academically defensible, thereby reinforcing the reliability and depth of the thematic.

2.2.2. Validation through industry reports

Industry white papers, operational audits, and corporate sustainability disclosures were examined to confirm the practical relevance of the coded patterns. Comparing the study's findings with these industry-specific documents helped verify the authenticity of reported benefits such as enhanced efficiency, predictive maintenance, and emission reduction. This step ensured that the

conclusions drawn were not solely theoretical but supported by real-world industrial data.

2.2.3. Validation through SDGs

Sustainable development goals were integrated into the triangulation process to evaluate the environmental and societal relevance of technological adoption. By benchmarking company initiatives against specific SDGs, such as climate action, affordable and clean energy, and responsible consumption and production, the study assessed whether the implementation of Industry 4.0 and 5.0 technologies contributed meaningfully to global sustainability targets. This approach also incorporated diverse stakeholder perspectives, ranging from regulatory bodies to community impact, thereby enriching the contextual depth of the analysis. The alignment with some sections of the SDGs ensured that the study's conclusions were not only operationally grounded but also socially and environmentally relevant.

Sections 7, 8, 9, 12, and 13 of the UN SDGs emphasize sustainable progress. Goal 7 promotes affordable, reliable, and clean energy. Goal 8 supports inclusive economic growth, decent work, and productivity. Goal 9 advances resilient infrastructure, industrialization, and innovation. Goal 12 advocates responsible consumption and production to reduce waste. Goal 13 urges urgent climate action, enhancing resilience and mitigation strategies to combat global warming and safeguard ecosystems for future generations [19]. Together, these goals create a unified framework that drives the transition toward sustainable development by linking clean energy, economic growth, innovation, resource efficiency, and climate resilience.

2.3. Outcome discussion and analysis

The final stage integrated the validated and benchmarked themes into a comprehensive results framework. The discussion interprets these themes in relation to operational outcomes, regional variations, and managerial implications. This synthesis not only connects empirical evidence to theoretical insights but also informs the strategic recommendations offered for sustainable digital transformation in oil and gas operations.

3. Results and discussion

Tables 3 and 4 present case studies of leading organizations that have successfully leveraged Industry 4.0 and 5.0 technologies, highlighting how they have improved operational efficiency, resilience, and sustainability across various domains, thereby setting a benchmark for industry transformation.

3.1. Case study of global organizations that have leveraged Industry 4.0 and 5.0 for their operational resilience

Table 3 presents how companies have effectively leveraged Industry 4.0 and Industry 5.0 technologies to enhance resiliency in their operations.

3.2. Case study of global organizations that have leveraged Industry 4.0 and 5.0 for their operational sustainability

Table 4 provides how leading oil and gas companies have strategically adopted Industry 4.0 and 5.0 technologies to enhance operational sustainability.

Table 3. Resilience case studies

Overview	Resiliency impact/benefits	Technology involved	Challenges
BP's use of AI and digital twins in offshore operations			
When it comes to leveraging AI and digital twins to streamline its offshore operations, BP has led the way. With the use of digital twins, which are replicas of actual assets, BP is able to model various situations and anticipate any problems before they occur	By using a predictive maintenance strategy, BP has been able to minimize maintenance costs by about 20 % while increasing equipment uptime. Additionally, by lowering the possibility of catastrophic equipment failures, it has increased safety [20]	<ul style="list-style-type: none"> – Digital twins were used to simulate situations and forecast possible equipment malfunctions – IoT for real-time performance tracking of offshore equipment – AI was used to streamline decision-making and maintenance schedules 	<ul style="list-style-type: none"> – High initial cost of digital twin deployment – Need for robust cybersecurity and data governance – Skills gap in managing complex AI models
TotalEnergies' use of AI for seismic data interpretation			
Artificial intelligence has been used by TotalEnergies, a French multinational integrated energy company to enhance seismic data interpretation, a critical process for oil exploration	TotalEnergies has drastically decreased the amount of time needed to analyze subsurface structures by using AI algorithms for seismic data. This has improved the precision of oil and gas exploration, which has decreased environmental impact and increased the success of drilling operations. It has also raised the success rate of finding viable reserves and reduced the cost of exploration [21]	<ul style="list-style-type: none"> – ML was used to improve seismic data analysis accuracy for oil exploration – Processing massive amounts of seismic data using big data analytics helped discover promising reserves – AI was applied to cut down on the expenses and time needed to interpret seismic data 	<ul style="list-style-type: none"> – Dependence on high-quality, large datasets – Integration challenges with legacy seismic systems – Data privacy and intellectual property concerns
Saudi Aramco's implementation of advanced analytics for energy optimization			
The largest oil producer in the world, Saudi Aramco, has implemented advanced data analytics to optimize energy usage throughout its operations. This covers the procedures for drilling, refining, and transportation	Aramco has decreased operating expenses, minimized its carbon footprint, and increased energy efficiency by employing advanced analytics to monitor and control energy use through the assurance of sustainable energy usage, even in times of varying market demand. This effort has improved operational resilience [22]	<ul style="list-style-type: none"> – Advanced analytics was employed to track and control energy usage throughout the company's operations – AI to maximize energy use in drilling, transportation, and refining operations – IoT for real-time data gathering to increase energy efficiency 	<ul style="list-style-type: none"> – Complex data integration across multiple sites – Continuous validation of large datasets – Organizational resistance to digital process changes
Woodside Energy's use of ML for predictive analytics			
The biggest natural gas producer in Australia, Woodside Energy, has incorporated ML models into its workflows to anticipate equipment malfunction and enhance production processes	Significant gains in operational efficiency have been made possible by Woodside's ML systems. Woodside has decreased unscheduled downtime, improved maintenance schedules, and raised overall production reliability by anticipating equipment failures before they occur. The company's capacity to sustain steady operations even in difficult market situations has improved because of this predictive strategy [23]	<ul style="list-style-type: none"> – Predicting equipment breakdowns was done with ML – Big Data analytics was used to analyze production data and improve workflows – IoT was used to improve real-time monitoring and data collecting for preventive maintenance 	<ul style="list-style-type: none"> – High data management and storage costs – ML model accuracy depends on data quality – Workforce adaptation and digital training needs

Repsol's real-time drilling optimization system			
<p>The Spanish oil and petrochemical company Repsol has put in place a real-time drilling optimization system that optimizes drilling parameters using AI and data analytics</p>	<p>Repsol's technology has increased drilling operations' precision and effectiveness while lowering the possibility of costly errors and cutting down on non-productive time (NPT). Repsol's drilling operations are now more robust to unforeseen geological problems and have resulted in considerable cost reductions due to its capacity to adjust to real-time data [24]</p>	<ul style="list-style-type: none"> - AI was employed for drilling parameter optimization to cut down on idle time - Drilling operations modification was done using real-time data analytics - IoT-enabled ongoing drilling activity monitoring to boost productivity 	<ul style="list-style-type: none"> - Data transmission limitations in remote areas - Integration with traditional drilling control systems - High maintenance cost of real-time sensors
Gazprom Neft's use of AI for drilling optimization			
<p>Artificial intelligence has been used by the Russian oil major Gazprom Neft to enhance drilling operations, especially in difficult geological conditions like the Arctic</p>	<p>Drilling time and expenses are substantially reduced by using AI-powered systems that evaluate data in real-time and modify drilling settings based on geological conditions. Gazprom Neft's operations are now more resilient, which enables the company to adjust to changing conditions and maximize resource exploitation [25]</p>	<ul style="list-style-type: none"> - AI was used to modify drilling settings in response to current geological data - Real-time data analytics for IoT-challenged drilling operations optimization - Real-time data gathering and analytics were employed to provide flexible drilling techniques 	<ul style="list-style-type: none"> - Harsh environmental conditions impacting data reliability - Limited communication infrastructure in Arctic regions - High cost of advanced AI model deployment
Marathon Oil's digital workforce with AR			
<p>Augmented reality technology has been utilized by Marathon Oil to provide real-time data and facilitate remote collaboration among its field personnel during challenging maintenance and repair tasks</p>	<p>Augmented Reality technology has been used by Marathon Oil to provide real-time data and remote collaboration to its field personnel during difficult maintenance and repair tasks, improving response efficiency, reducing downtime, and strengthening workforce adaptability [26]</p>	<ul style="list-style-type: none"> - Field workers were assisted with real-time data during maintenance operations by using AR - AI was employed to improve remote decision-making and cooperation - Field personnel received real-time sensor data via IoT for improved troubleshooting 	<ul style="list-style-type: none"> - High hardware and connectivity costs in field operations - Resistance to AR adoption among field technicians - Data synchronization issues in low-network zones
Baker Hughes' smart valves with IoT and AI			
<p>Global oilfield services provider Baker Hughes has created smart valves that use AI algorithms and IoT sensors to optimise the flow of gas and oil in real-time</p>	<p>To automatically modify valve settings, AI systems analyze the pressure, temperature, and flow rate data that smart valves continually gather. With the use of this technology, Baker Hughes' operations are more robust and flexible to changing field conditions. This initiative lowers the risk of leaks, increasing production efficiency, and improving safety [27]</p>	<ul style="list-style-type: none"> - IoT was employed to track flow rates, temperature, and pressure in real time - AI modified valve settings automatically to maximize flow - Smart valves lowered the possibility of leaks to improve safety and production efficiency 	<ul style="list-style-type: none"> - Complex calibration and maintenance requirements - High initial deployment cost - Cybersecurity vulnerabilities in connected systems
Halliburton's advanced robotics for fracking			

For the purpose of increasing productivity and minimizing human exposure to dangerous conditions, Halliburton has implemented robots and automation in its hydraulic fracturing (fracking) operations	Numerous manual fracking operations, such as fluid management and pipe handling, are automated by robots, which lowers the danger of accidents and increases operational efficiency. Halliburton's fracking processes are now more robust and scalable because of the deployment of robots, which have also improved safety, reduced operational interruptions, and guaranteed more uniformity [28]	<ul style="list-style-type: none"> – Robotics was used to replace human labour in hydraulic fracturing operations – Automation was employed to boost fracking efficiency and security – AI was used to improve uniformity and reduce fracking operation disturbances 	<ul style="list-style-type: none"> – High capital and maintenance costs for robotics systems – Limited interoperability with older fracking equipment – Need for specialized robotics engineers
Schlumberger's cloud-based reservoir modelling with AI			
To optimize the extraction process, Schlumberger has created cloud-based reservoir modeling tools that mimic oil and gas reservoirs in real-time using AI and advanced analytics	Engineers can simulate and forecast reservoir behaviour under various extraction situations with the help of these AI-driven models. By extending reservoir life, reducing risks, and optimizing output, Schlumberger is able to create a more robust operation that is more able to adjust to changes in market circumstances and reservoir performance [29]	<ul style="list-style-type: none"> – Cloud computing was used to simulate real-time reservoir behaviour – AI was used to forecast reservoir performance and optimize extraction procedures – Big data analytics was used to examine how reservoir data can prolong reservoir life and reduce hazards 	<ul style="list-style-type: none"> – Dependence on reliable high-speed internet infrastructure – Data security and confidentiality risks in cloud platforms – High computational costs for large-scale simulations

Table 4. Sustainability case studies

Overview	Sustainability Impact/benefits	Technology involved	Challenges
Adnoc's Panorama Digital Command Centre (UAE)			
The Panorama digital command centre is a centralized hub designed to optimize operations, enhance sustainability, and improve efficiency across its value chain. It integrates data from upstream, midstream, and downstream operations, analyzing over 200 million daily data points from sensors, IoT devices, and digital systems.	The Panorama Digital Command Center has enhanced Adnoc's operations by improving energy efficiency, reducing costs, and optimizing operational processes. It has achieved over \$1 billion in savings, improved environmental compliance, and minimized the operational footprint through real-time monitoring and analytics. Additionally, it strengthens resilience by proactively identifying risks and implementing strategies to mitigate disruptions, ensuring adaptability to market change [30]	<ul style="list-style-type: none"> – It uses Big Data Analytics to process vast operational data – AI for predictive maintenance and optimization – IoT and Edge Computing for real-time data collection – Advanced visualization tools for better decision-making and complex data understanding 	<ul style="list-style-type: none"> – Integration challenges with legacy systems – High implementation and data management costs – Ensuring cybersecurity and data privacy
OMV's ReOil plastic recycling project			

<p>The ReOil initiative, which aimed to convert plastic waste into synthetic crude oil, was created by the Austrian oil and gas corporation OMV. OMV is dedicated to the circular economy and the reduction of plastic waste, which includes this creative recycling method</p>	<p>The ReOil initiative provides a sustainable way to manage plastic waste by transforming it into a valuable resource. By refining the synthetic crude oil produced from plastic waste into fuel or other chemical products, it helps decrease the reliance on new fossil resources and minimizes the environmental impact associated with plastic disposal [31]</p>	<ul style="list-style-type: none"> – AI-powered process control to maximize the conversion of plastic to oil – Robots were used for automatically process and sort plastic waste – IoT sensors for real-time monitoring and control of recycling processes 	<ul style="list-style-type: none"> – High processing costs for large-scale deployment – Variability in feedstock quality – Regulatory challenges for recycled fuel certification
<p>Enbridge’s renewable natural gas (RNG) projects</p>			
<p>As part of its plan to lower carbon emissions, Enbridge, a North American energy infrastructure firm, has been investing in renewable natural gas, or RNG. Organic waste from landfills, wastewater treatment facilities, and agricultural leftovers is used to make RNG</p>	<p>Through the capture and reuse of biogas that would otherwise be released into the atmosphere, Enbridge's RNG initiatives contributed to a reduction in methane emissions. The company's RNG facilities aid in the switch to sustainable energy by offering a low-carbon substitute for traditional natural gas [32].</p>	<ul style="list-style-type: none"> – AI-powered resource management and biogas production optimization – Real-time monitoring of the productivity and quality of biogas production using IoT – Blockchain was used for tracking the production and distribution of RNGs securely and transparently 	<ul style="list-style-type: none"> – Complex integration with existing gas networks – Limited feedstock availability – High cost of RNG infrastructure
<p>ConocoPhillips’ sustainable development scorecard</p>			
<p>A Sustainable Development Scorecard was created by ConocoPhillips to monitor and report on its performance in social responsibility, economic development, and environmental management. A larger commitment to transparent reporting and sustainable development is made by the organization, which includes the scorecard</p>	<p>The scorecard includes metrics on water use, spill avoidance, greenhouse gas emissions, and community involvement. ConocoPhillips utilizes this data to convey its sustainability status to stakeholders and pinpoint areas for improvement [33]</p>	<ul style="list-style-type: none"> – AI was utilized to forecast and analyze sustainability parameters – Advanced data analytics facilitate real-time monitoring of the environment – Blockchain technology guarantees transparent and secure reporting of sustainability data 	<ul style="list-style-type: none"> – Data harmonization across regions – High cost of continuous monitoring – Difficulty quantifying social impact metrics
<p>TechnipFMC’s Subsea Processing Technology (Norway)</p>			
<p>TechnipFMC’s subsea processing technology is a revolutionary step in the oil and gas sector, particularly for offshore operations. By shifting key processing functions from surface platforms to subsea facilities, this technology not only reduces costs and carbon emissions but also improves the efficiency and safety of offshore oil and gas production</p>	<p>This technology extends field life, reduces resource depletion, and supports renewable energy integration, enhancing sustainability [34]</p>	<ul style="list-style-type: none"> – AI optimizes operations through predictive analytics – IoT sensors monitor critical parameters for real-time adjustments and predictive maintenance – Automation minimizes human error, enhances efficiency, and improves safety in hazardous subsea environments 	<ul style="list-style-type: none"> – Technical complexity of subsea integration – High capital expenditure – Maintenance difficulties in deep-sea environments
<p>Eni’s circular economy and waste-to-energy projects</p>			

<p>The Italian oil and gas corporation, Eni, has been investigating the ideas of the circular economy by creating waste-to-energy initiatives. Eni's bio-refinery in Venice is one of such projects that turns used cooking oil and other waste materials into biodiesel</p>	<p>Eni's circular economy initiatives turn waste into useful energy products, which reduces greenhouse gas emissions and waste. For instance, biodiesel produced at the bio-refinery in Venice is more sustainable and cleaner than traditional diesel fuel [35]</p>	<ul style="list-style-type: none"> - AI was used to maximize waste-to-energy conversion and bio-refinery processes - Robotics was used to automate waste material processing - IoT for monitoring and controlling energy outputs and waste streams in real-time 	<ul style="list-style-type: none"> - Supply chain limitations for waste collection - Energy efficiency challenges - Regulatory compliance for biofuel standards
<p>Chevron's renewable energy investments</p>			
<p>As part of a larger plan to diversify its energy portfolio, Chevron has invested in renewable energy projects. The company has made large global investments in wind, solar, and geothermal energy projects</p>	<p>Chevron's geothermal initiatives, including those in the Philippines and Indonesia, offer a reliable and sustainable energy source that lessens dependency on fossil fuels. Furthermore, Chevron's solar and wind energy initiatives support the global shift to sustainable energy sources [36]</p>	<ul style="list-style-type: none"> - AI was used to maximize wind, solar, and geothermal energy system performance - Monitoring of renewable energy installations was made possible by IoT - Advanced data analytics was used for energy forecasting and predictive maintenance 	<ul style="list-style-type: none"> - Intermittency of renewable sources - Integration into conventional grid systems - Market volatility and policy uncertainty
<p>Equinor's Hywind Scotland offshore wind farm</p>			
<p>The world's first floating offshore wind farm, called Hywind Scotland, was created by Equinor, formerly known as Statoil, and it started operating in 2017. Five floating turbines off the coast of Scotland make up the project, which supplies over 20,000 houses with sustainable energy</p>	<p>Hywind Scotland demonstrates how oil and gas companies can leverage their offshore expertise to develop renewable energy projects. By replacing fossil fuel-generated power with wind energy, the wind farm has contributed to reducing carbon emissions [37]</p>	<ul style="list-style-type: none"> - AI was used to maximize energy output and wind turbine performance - IoT-enabled operations and condition monitoring of offshore wind farms - Robotics was used for offshore wind turbine inspection and maintenance 	<ul style="list-style-type: none"> - High capital and maintenance costs - Harsh offshore weather conditions - Limited global experience with floating wind technology
<p>ExxonMobil's algae biofuels initiative</p>			
<p>Algae biofuels are a sustainable substitute for traditional fossil fuels that ExxonMobil has been investigating and developing. The company worked with Synthetic Genomics to genetically modify algae strains that generate large amounts of biofuels, which are then processed into jet fuel, diesel, and petrol</p>	<p>Because algae can be produced using CO₂, sunshine, and water, they have the potential to drastically cut greenhouse gas emissions when compared to traditional fossil fuels. The goal of ExxonMobil's project was to lessen the environmental effect of fuel production while increasing output to meet the global need for energy [38]</p>	<ul style="list-style-type: none"> - AI was used to enhance the processes involved in producing biofuel and cultivating algae - IoT sensors tracked the conditions for algal growth and the output of biofuel - MI improved the genetic engineering of algal strains 	<ul style="list-style-type: none"> - High production costs - Scalability and commercialization challenges - Long development timelines
<p>Shell's Quest carbon capture and storage (CCS) project</p>			

<p>The Quest Carbon Capture and Storage (CCS) project, initiated by Shell in 2015 in Alberta, Canada, is an innovative endeavour to decrease greenhouse gas emissions from oil sands activities. The project stores CO₂ underground in a saline aquifer, capturing it during the bitumen upgrading process, which is a step in the development of oil sands</p>	<p>The Quest project captures and stores more than a million tonnes of CO₂ annually, which is equivalent to the emissions from 250,000 cars. Through the use of technologies that have the potential to significantly reduce carbon emissions from its operations, Shell is showcasing its dedication to addressing climate change [39]</p>	<p>– AI was utilized to optimize the processes of CO₂ storage, compression, and capture – IoT devices were employed to monitor CO₂ levels and storage conditions in real-time – Advanced analytics were applied for predictive maintenance of CCS infrastructure</p>	<p>– High operational and maintenance costs – Uncertainty in long-term CO₂ storage integrity – Public acceptance and regulatory constraints</p>
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3.3. Case studies analysis: Industry 4.0 and 5.0 technologies driving resilience and sustainability in global oil and gas operations

The reviewed case studies on resilience and sustainability illustrate how global oil and gas companies are strategically adopting Industry 4.0 and 5.0 technologies to strengthen operational performance, environmental stewardship, and long-term adaptability. Across organizations such as BP, TotalEnergies, Saudi Aramco, Woodside, Repsol, Gazprom Neft, Marathon Oil, Baker Hughes, Halliburton, Schlumberger, Adnoc, OMV, Enbridge, ConocoPhillips, TechnipFMC, Eni, Chevron, Equinor, ExxonMobil, and Shell, it is evident that the integration of digital innovations, such as AI, ML, IoT, robotics, AR, and cloud analytics, has become central to achieving both operational resilience and sustainability. These technologies have enabled real-time decision-making, predictive maintenance, optimized energy use, improved safety, and reduced environmental footprints, reinforcing the industry’s capacity to adapt to evolving challenges and market conditions.

The benefits observed across these initiatives are extensive. From a resilience standpoint, digital twins, advanced analytics, and AI-driven predictive maintenance have significantly reduced unplanned downtime, optimized maintenance scheduling, and improved equipment reliability. For example, BP’s use of digital twins and AI has reduced maintenance costs and improved asset uptime, while Saudi Aramco’s deployment of advanced analytics has enhanced energy efficiency and minimized its carbon footprint. Sustainability-focused projects have also delivered remarkable gains. Initiatives such as Adnoc’s Panorama Digital Command Center and Shell’s Quest Carbon Capture and Storage project demonstrate measurable progress in emission reduction, energy optimization, and responsible resource management. Similarly, companies like OMV and Eni have advanced circular economy principles by converting waste into reusable energy resources, while Equinor’s Hywind Scotland wind farm and Chevron’s renewable energy investments showcase successful transitions toward clean energy.

However, the implementation of these technologies is not without challenges. One of the most significant obstacles is the high capital and operational costs associated with adopting digital and green technologies. The deployment of AI systems, IoT networks, and robotics requires substantial investment in hardware, software, and skilled labor. Additionally, integration with legacy systems remains a persistent difficulty, as older infrastructure often lacks compatibility with modern digital tools, resulting in inefficiencies and data silos. Data quality and governance issues also hinder predictive accuracy, while cybersecurity risks continue to grow as operations become more interconnected. Furthermore, the shortage of skilled digital professionals and organizational resistance to change slow the pace of technological adoption. In sustainability projects, technical complexities, regulatory uncertainties, and harsh operating environments, such as deep-sea and Arctic conditions, pose further challenges to continuous operation and monitoring.

To address these challenges, several recommendations are proposed. From a technical and data management perspective, companies should adopt a phased implementation strategy that begins

with high-impact pilot projects to demonstrate measurable return on investment before large-scale deployment. A modular and interoperable integration architecture should be established to ensure seamless data flow between legacy and new systems, supported by strong data governance frameworks that define ownership, quality standards, and cybersecurity strategies. In addition, hybrid computing models combining edge and cloud computing can mitigate connectivity limitations in remote areas while maintaining real-time data processing and analytics capabilities.

From a cybersecurity and compliance standpoint, oil and gas firms should apply a defense-in-depth approach that incorporates network segmentation, identity-based access controls, and continuous threat monitoring to safeguard both operational and information technology systems. Third-party vendors should be subjected to regular security audits to prevent vulnerabilities across shared platforms. Furthermore, organizations must prioritize workforce development through targeted reskilling and cross-functional training programs that combine domain expertise with digital competencies. Establishing “digital apprenticeship” programs can bridge the gap between engineers and data scientists, fostering collaboration and innovation.

Change management is another critical factor for successful adoption. Leadership should communicate the benefits of digital transformation clearly, highlight early successes, and involve employees at all levels in the transition process to reduce resistance. Financially, firms can leverage performance-based contracts, public-private partnerships, and blended financing models to reduce upfront costs and spread investment risks. Collaboration with regulatory bodies and industry consortia can also help establish standardized protocols, enhance interoperability, and accelerate regulatory approval processes for new technologies such as recycled fuels and CCS systems.

From an operational resilience perspective, companies operating in harsh environments should prioritize sensor redundancy, robust communication infrastructure, and adaptive data synchronization strategies to maintain reliability under extreme conditions. Periodic validation of large datasets is essential to ensure model accuracy and consistency across sites. For sustainability initiatives, organizations should adopt transparent reporting systems using blockchain or advanced data analytics to track emissions, energy intensity, and waste reduction metrics, thereby enhancing stakeholder trust and compliance with global standards.

It is worth noting that despite the inclusion of implementation challenges within the case study summaries, it is important to recognize that the selection of documented examples may still be subject to biases. Successful cases are often more likely to be reported, potentially leading to an overestimation of positive outcomes and underrepresentation of failures or setbacks. Future research should strive to incorporate a more comprehensive range of experiences, including unsuccessful implementations, to develop a balanced understanding of the barriers and practical realities faced in deploying Industry 4.0 and 5.0 technologies.

Conclusively, the analyzed case studies demonstrate that the integration of Industry 4.0 and 5.0 technologies has become a powerful enabler of resilience and sustainability in the oil and gas industry. The key to maximizing these benefits lies in strategic investment, data-driven decision-making, skilled workforce development, and proactive policy alignment. By addressing cost, integration, cybersecurity, and talent challenges through the recommended strategies, companies can transform technological innovation into lasting business value, environmental responsibility, and long-term operational resilience.

3.4. Challenges and contextual adaptation of Industry 4.0 and 5.0 technologies in developing oil and gas economies

While global leaders in oil and operations are making substantial progress in adopting Industry 4.0 and 5.0, the experience in developing regions, particularly among small and medium-sized enterprises (SMEs), differs considerably due to structural, economic, and institutional constraints.

A peculiar challenge in developing regions is the inadequacy of digital and physical infrastructure needed to sustain Industry 4.0 and 5.0 systems. Many smaller enterprises operate in

environments characterized by unstable electricity supply, weak broadband connectivity, and limited access to modern data centers. These conditions make it difficult to deploy real-time data acquisition systems or cloud-based analytics. In contrast, global leaders such as Adnoc operate centralized digital command centres, an option unavailable to most SMEs in developing economies. To mitigate these challenges, edge computing and hybrid data processing solutions can be adopted to minimize reliance on continuous internet connectivity. Regional governments and private investors can also collaborate to develop shared digital infrastructure, such as data hubs and renewable microgrids to enhance industrial productivity.

Another major constraint is the high cost of implementation and maintenance associated with digital transformation. While multinational corporations can sustain multimillion-dollar investments in automation, robotics, and cloud infrastructure, SMEs in developing regions operate within tight financial limits. The prohibitive cost of sensors, analytics software, and cybersecurity systems discourages smaller enterprises from initiating transformation projects. This situation mirrors the high capital requirements observed in the sustainability case studies but is magnified by restricted access to credit and the absence of financial incentives. Overcoming this barrier requires phased or modular digital transformation strategies that begin with affordable pilot projects capable of demonstrating measurable returns before scaling up. Governments and international agencies should provide technology adoption grants, concessional financing, and tax incentives to encourage SMEs to invest in smart and sustainable innovations.

Skill shortages and workforce readiness also remain critical barriers. Even among global oil and gas leaders, case studies revealed gaps in digital expertise, particularly in integrating and managing Industry 4.0 and 5.0 technologies. In developing economies, this challenge is far more pronounced. Many small enterprises lack qualified personnel such as data analysts, system integrators, and maintenance technologists, which hinders effective technology utilization. The reliance on foreign consultants further increases costs and limits local capacity development. Addressing this challenge calls for the establishment of vocational and digital training programs through partnerships between governments, universities, and industry associations. Apprenticeship schemes that pair local engineers with global experts during system deployment can also promote hands-on knowledge transfer.

Data quality, integration, and cybersecurity risks present additional complications. In most developing regions, small enterprises rely on fragmented manual systems and lack structured data governance frameworks, making it difficult to achieve the data accuracy and reliability required for predictive analytics. These deficiencies also increase exposure to cyber threats. Large corporations have responded by developing robust cybersecurity strategies, yet smaller firms often lack such resources. To address this, national policies promoting data standardization, interoperability, and cybersecurity awareness should be prioritized. Affordable, cloud-based data protection services can also be developed to support smaller organizations and strengthen trust in digital operations.

Regulatory and policy limitations further complicate digital adoption. Many developing regions lack comprehensive industrial digitalization policies, standards, or incentives aligned with Industry 4.0 and 5.0 frameworks. Outdated energy regulations, high import tariffs on digital equipment, and weak intellectual property protections discourage investment and innovation. Unlike multinational firms operating under clear compliance standards, SMEs face inconsistent or poorly enforced regulations. To resolve this, governments must formulate national digital industrialization roadmaps that align with global sustainability frameworks such as the UN Sustainable Development Goals and the Paris Climate Agreement. Innovation sandboxes, controlled environments that allow organizations to experiment with emerging technologies, can also accelerate adoption while minimizing risk.

Cultural and organizational resistance to change represents another subtle but significant barrier. In smaller enterprises, digital adoption is often perceived as a threat to employment or as an unnecessary luxury. Limited managerial exposure to technology-driven business models leads to skepticism about return on investment, further delaying implementation. This resistance mirrors

challenges noted in global sustainability case studies, where even large firms experienced reluctance during digital transitions. Overcoming this barrier requires inclusive change management approaches that emphasize employee involvement, transparency, and demonstration of tangible benefits such as reduced downtime or improved safety. The human-centric philosophy of Industry 5.0, which prioritizes collaboration between humans and machines, offers a framework for integrating technology without undermining the workforce.

When connected to the sustainability and resilience case study analysis, it becomes evident that the same types of challenges, high cost, and data management issues, cybersecurity risks, and workforce limitations, exist across both global and developing contexts, though the intensity and scale differ. The primary distinction lies in access to resources, institutional support, and readiness levels. The strategies identified in global case studies, such as modular digital adoption, workforce reskilling, data governance, and hybrid power systems, remain relevant but require contextual adaptation for smaller enterprises. Instead of centralized command centres, SMEs in developing economies could leverage shared digital platforms or cooperative data hubs. Similarly, cloud-based analytics and open-source tools can serve as cost-effective alternatives to in-house digital infrastructure.

Ultimately, the successful implementation of Industry 4.0 and 5.0 technologies in developing regions depends on aligning global best practices with local realities. By addressing infrastructural deficits, enhancing workforce capabilities, improving policy frameworks, and promoting collaborative investment, smaller enterprises can gradually unlock the sustainability and resilience benefits demonstrated by leading global firms. The transition must therefore be inclusive, scalable, and human-centred to ensure that the technological revolution contributes to both long-term economic growth and environmental sustainability.

3.5. Impact of geographical location on the adoption of Industry 4.0 and 5.0 in the oil and gas sector

The adoption of Industry 4.0 and Industry 5.0 in the oil and gas sector is greatly affected by geographical location, this is highlighted in Table 5. Several factors, including regional regulatory frameworks, infrastructure development, economic conditions, technological readiness, and environmental challenges, determine the degree to which these advanced industrial paradigms are adopted. Analyzing 20 leading oil and gas companies from various regions provides valuable insights into the impact of geography on technological integration.

By implementing these measures, oil and gas companies across various regions can accelerate their digital transformation, improve operational efficiency, and remain competitive in an evolving global energy landscape.

3.6. Strategic framework for the adoption of Industry 4.0 and 5.0 technologies in the oil and gas sector

Building on the adoption barriers and strategic recommendations discussed above, this study proposes a comprehensive framework to guide the integration of Industry 4.0 and 5.0 technologies in the oil and gas sector. Fig. 2 illustrates a framework that consolidates the key findings into a structured flow, beginning with foundational pillars, progressing through stages of adoption, supported by enabling factors, and culminating in measurable outcomes. This visual representation illustrates how technological adoption can be systematically aligned with sustainability goals while overcoming critical implementation challenges.

Table 5. Impact of geographical location on the adoption of Industry 4.0 and 5.0

Region	Example companies	Key factors impacting adoption	Recommendations to enhance adoption
North America	ConocoPhillips, Enbridge	<ul style="list-style-type: none"> – Strong digital infrastructure: Well-developed cloud computing, high-speed internet, and widespread adoption of IoT devices – Regulatory support for innovation: Governments encourage automation, AI, and sustainability-focused R&D through policies and incentives – High investment in automation and AI: Companies allocate significant budgets to cutting-edge technology adoption, ensuring rapid implementation 	<ul style="list-style-type: none"> – Strengthen cross-sector partnerships: Expand collaboration between oil and gas companies, AI startups, and universities to accelerate innovation – Prioritize cybersecurity: Invest in robust cybersecurity frameworks to protect digital infrastructure and IoT networks – Promote workforce upskilling: Implement continuous digital training programs to align employees with rapid AI and automation advances
Europe	TotalEnergies, Schlumberger	<ul style="list-style-type: none"> – Sustainability-driven regulations: The European Union mandates strict environmental policies, pushing companies toward cleaner and more efficient operations – Advanced workforce skills: Highly skilled labor force trained in automation and AI – Cross-industry digital collaboration: European firms actively collaborate with tech companies and research institutions to drive innovation 	<ul style="list-style-type: none"> – Enhance regulatory alignment: Work with EU regulators to streamline compliance while maintaining sustainability goals – Expand public-private innovation hubs: Foster stronger partnerships between governments, research institutions, and industry leaders – Scale green technologies: Prioritize investments in renewable energy integration and carbon-neutral digital solutions
Middle East	Saudi Aramco, ADNOC	<ul style="list-style-type: none"> – Abundant natural resources: Large oil and gas reserves drive a focus on maximizing resource extraction and operational efficiency – Geopolitical and sustainability pressures: Companies are adopting digitalization to balance energy security with global sustainability goals – Government-led digital initiatives: National strategies such as Saudi Vision 2030 push for AI, IoT, and automation adoption 	<ul style="list-style-type: none"> – Leverage government visions: Align digital strategies with national transformation plans like Saudi Vision 2030 and UAE’s digital initiatives – Diversify digital applications: Move beyond resource extraction to integrate digital twins, AI-driven maintenance, and energy efficiency tools – Develop local talent pipelines: Invest in training and scholarship programs to reduce reliance on foreign expertise
Russia	Gazprom	<ul style="list-style-type: none"> – Legacy infrastructure: Many oil and gas assets were developed during the Soviet era, making digital transformation more complex and requiring significant retrofitting – Regulatory and political constraints: Government policies influence technology imports, affecting Industry 4.0 adoption speed – Selective technology adoption: Focus on digital solutions that improve operational efficiency while working within regulatory and infrastructure constraints 	<ul style="list-style-type: none"> – Modernize legacy infrastructure: Adopt phased retrofitting strategies combining IoT, predictive analytics, and automation – Encourage technology partnerships: Engage with non-restricted technology providers to mitigate import constraints – Promote in-house R&D: Strengthen domestic research to reduce dependency on foreign digital tools

Asia-Pacific	TechnipFMC	<ul style="list-style-type: none"> – Harsh environments require predictive maintenance: Oil and gas operations in offshore and remote areas face extreme weather and operational stress, making predictive maintenance crucial to prevent failures, and ensure safety – Infrastructure gaps in remote areas: Limited digital infrastructure, poor connectivity, and logistical challenges in remote sites hinder the full deployment of advanced tech – High energy demand but uneven digital capacity: Rapidly growing energy demand across the region contrasts with inconsistent access to digital solutions, creating disparities in adoption levels and slowing large-scale implementation of Industry 4.0 and 5.0 technology 	<ul style="list-style-type: none"> – Invest in resilient digital infrastructure: Expand connectivity in remote and offshore regions – Adopt predictive maintenance at scale: Use AI-driven models to handle harsh environments and reduce downtime – Regional collaboration: Encourage technology-sharing platforms among Asia-Pacific nations to reduce uneven digital capacity
Africa	Affiliates (e.g., Nigerian National Petroleum Corporation - NNPC, Sonangol)	<ul style="list-style-type: none"> – Infrastructure challenges: Limited digital infrastructure and inconsistent internet connectivity slow down large-scale adoption of Industry 4.0 – Regulatory and policy gaps: Varying policies across African nations create uncertainty for large-scale automation and AI investments – Resource-driven investment: Digital adoption focuses on enhancing extraction and production efficiency rather than full automation. Skills gap and workforce training: Limited availability of local expertise in advanced digital technologies necessitates foreign expertise and partnerships 	<ul style="list-style-type: none"> – Strengthen digital infrastructure: Invest in internet backbone, cloud services, and reliable connectivity – Create unified policies: Harmonize regional regulatory frameworks to reduce uncertainty for investors – Develop local capacity: Establish training centers and digital academies to bridge the skills gap. Encourage joint ventures: Promote partnerships with global firms to transfer technology and knowledge locally

The visual diagram presents a structured framework for the adoption of Industry 4.0 and 5.0 technologies in the oil and gas sector, highlighting the interconnections between foundational pillars, adoption stages, enablers, and expected outcomes. At the top, the foundational pillars such as technological integration, human-machine collaboration, sustainability alignment with the UN SDGs, and resilience building, serve as guiding principles that establish the direction of digital transformation. Flowing from these pillars are the stages of adoption, which progress logically from assessing readiness and building digital infrastructure to workforce upskilling, operational integration, sustainability alignment, and continuous innovation. Surrounding this pathway are the enablers, including governance and regulation, financial mechanisms, collaborative networks, and ethical safeguards, which act as cross-cutting supports to strengthen each stage. After achieving the expected outcomes through the structured stages of adoption, the next steps are agile management, which involves continuous improvement, monitoring, and strategic evolution to sustain and enhance digital transformation benefits. The arrows emphasize this progression, illustrating how foundations guide adoption, enablers provide support, and structured adoption ultimately delivers measurable outcomes. These outcomes include enhanced operational efficiency, improved safety and resilience, environmental stewardship, and strengthened global competitiveness. Collectively, the diagram communicates a holistic strategy, showing that successful adoption depends not only on technology but also on alignment with sustainability

goals, robust enablers, and a commitment to long-term transformation.

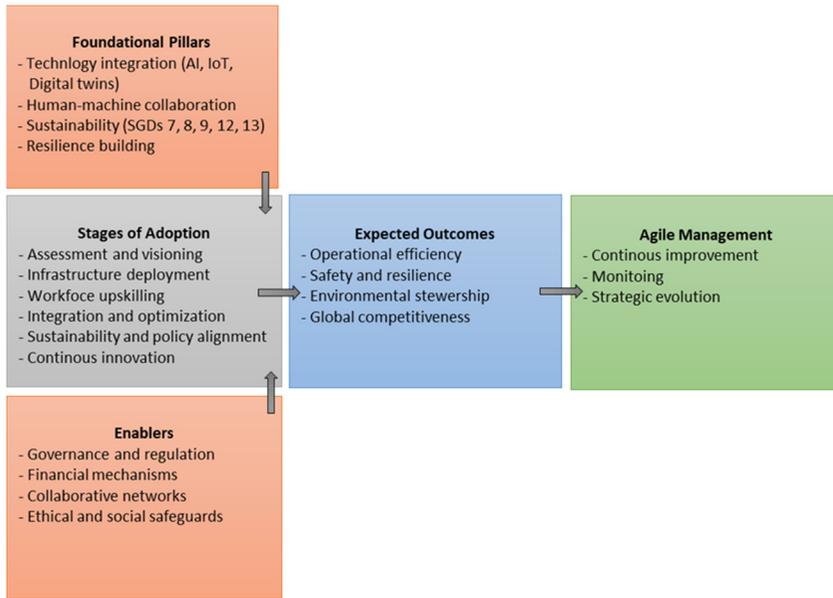


Fig. 2. Framework for the adoption of Industry 4.0 and 5.0 technologies in the oil and gas sector

3.7. Ethical concerns about workforce displacement

The rapid adoption of Industry 4.0 and 5.0 technologies has raised ethical concerns regarding workforce displacement, particularly in labour-intensive industries like oil and gas. Automation, AI, and robotics replace tasks traditionally performed by humans, leading to job losses, especially for workers with limited education or specialized skills. For instance, autonomous systems, predictive maintenance tools, and robotic process automation can perform tasks such as equipment inspection, data logging, and production line monitoring more efficiently than humans. While this improves operational efficiency, it reduces the demand for roles requiring manual intervention.

This displacement disproportionately affects workers in developing regions, where industries rely heavily on manual labor. Many workers lack access to upskilling or reskilling programs that would enable them to transition into roles compatible with these advanced technologies. As a result, they face long-term unemployment and economic hardship, exacerbating income inequality and social instability.

Another ethical concern is the dehumanization of labour. In highly automated environments, workers who remain employed may experience diminished job satisfaction as repetitive, low-value tasks are replaced by human-machine collaboration that prioritizes precision over creativity. This shift can create a sense of alienation among workers, as their roles become secondary to machines' capabilities.

Moreover, decision-making increasingly relies on AI systems, which can perpetuate biases if not properly designed. Algorithms may unintentionally favour certain demographics or skill sets, further marginalizing underrepresented groups in the workforce. Additionally, workers may face surveillance and data privacy issues as IoT-enabled systems and wearable devices collect real-time data on performance and productivity. Such monitoring, if mismanaged, can erode trust between employers and employees, leading to workplace dissatisfaction.

To address these concerns, it is essential to prioritize human-centric strategies inherent in Industry 5.0. Organizations should invest in training and upskilling programs to prepare workers for higher-value tasks, such as managing, programming, and maintaining automated systems. Governments and companies must collaborate to create social safety nets, including

unemployment benefits and transitional support for displaced workers, Ethical guidelines should be established to ensure that technology adoption respects workers' rights and promotes inclusive growth.

3.8. Recommendations for future research

Building on the study's findings, a strategic research approach is essential to propel advancements in this field. This requires targeted investments in scalable technology adoption, workforce up-skilling, sustainability-driven innovations, and empirical validation through predictive analytics. By integrating these elements, the oil and gas industry can achieve greater resilience, operational efficiency, and long-term sustainability. Three of such specific future research recommendations are:

- 1) Enhancing cybersecurity frameworks for Industry 4.0 and 5.0 adoption in the oil and gas sector: This study will examine the vulnerabilities associated with integrating IoT, AI, and digital infrastructure, proposing robust security models for data protection and operational resilience.
- 2) The Impact of AI-driven predictive maintenance on sustainability and cost reduction in oil and gas operations: This research will quantitatively assess how predictive analytics and machine learning optimize maintenance strategies, reduce downtime, and minimize environmental impact.
- 3) Workforce readiness for Industry 5.0 in the oil and gas industry: This study will examine the required skill sets for effective human-machine collaboration, proposing training frameworks to facilitate workforce adaptation in digitalized industrial environments.

4. Conclusions

This research draws attention to the essential role of Industry 4.0 and 5.0 technologies, such as AI, IoT, robotics, and digital twins, in promoting sustainability and resilience in the oil and gas industry. Practical case studies reveal benefits like predictive maintenance, energy efficiency, and reduced downtime, demonstrating their significance in sustainable development, resonating with insights from previous works like [8] and [9].

To support effective implementation and alignment with global sustainability targets, the study introduces a comprehensive strategic framework. This framework outlines key pillars, adoption phases, enabling factors, and measurable outcomes, guiding oil and gas companies through a structured digital transformation.

The study underscores human-machine collaboration and alignment with key UN SDGs, particularly SDGs 7, 8, 9, 12, and 13. It highlights pathways for clean energy, inclusive growth, innovation, responsible resource utilization, and climate resilience.

Furthermore, it fosters transformative global advancement by providing actionable strategies to address widespread challenges such as high implementation costs, workforce skill deficiencies, cybersecurity threats, financial constraints, data management inefficiencies, and regulatory barriers. Notably, these ecumbrances are evident in both global and developing contexts, differing mainly in their scale, resource availability, institutional support, and overall readiness levels.

By adopting this strategic approach, companies can enhance efficiency, manage risks, and support the broader transition toward a sustainable, innovation-driven energy sector.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Ahiamadu Jonathan Okirie: conceptualization, data collection, investigation, writing-original draft preparation, methodology, data analysis. Eleba Frank Lawson: validation, review and editing, methodology. Nyekachi Olumati Ozuru: validation, review and editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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