Digital Transformation of the Oil and Gas Sector Towards Decarbonizing the Energy System for Net Zero Emissions in the Gulf Region: Trends, Applications, Challenges and Enablers

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Abstract

This article explores digital transformation in the oil and gas sector within the context of the Gulf countries. It highlights the latest trends in Industry 4.0 technologies, along with other advances related to renewable energy, alternative fuels, carbon removal, methane abatement and flaring control. The article highlights the transformative abilities of these technologies in revolutionizing oil and gas operations and sculpting the forthcoming narrative of the Gulf region and beyond. The discussion also delves into the opportunities, applications, and real-world use cases highlighting how technologies are driving the clean energy transition. The challenges in transforming the sector are then examined, followed by recommendations of critical success factors as enablers for governments and national oil companies to decarbonize the energy system in the region in pursuit of accelerating the realization of the net zero emissions agenda.

1. The Net Zero Emissions Agenda

In 2016, the historic Paris Agreement adopted at COP21, was enacted with the main goal of combating climate change and accelerating the global response to its threats. The Paris treaty brought together 195 nations in a collective effort to limit global warming to < 2°C above pre-industrial levels, with an aspiration to further limit the increase to 1.5°C. To remain within the latter limit, global carbon dioxide (CO_2) emissions must be reduced by an estimated 45% by 2030 (relative to 2010 levels) and eventually reach net zero emissions (NZE) by 2050 [1]. NZE refers to a state where the amount of greenhouse gases (GHG) released into the atmosphere is balanced by an equivalent amount removed, effectively reducing the net impact on the climate to zero. Currently, a total of 148 countries pledged to achieve NZE with the majority targeting mid-century [2], necessitating an extensive transformation across various sectors of the energy system including power, buildings, transport, industry and agriculture. Hard-to-abate sectors have a vital role in meeting the Paris goals, and are particularly challenging to decarbonize due to their high energy intensity, reliance on fossil fuels, and limited availability of practical low-carbon alternatives or proven technologies [3]. Specifically, the clean energy transition implies the restructuring of production processes on the supply side of the energy system which are responsible for the bulk of emissions. As the backbone of the global energy landscape and the main source of primary energy, the oil and gas (O&G) sector is a major source of GHG emissions from combustion processes and methane leaks during extraction, processing, and transportation for final use. Today, O&G operations are responsible for around 15% of total energy-related emissions globally, the equivalent of 5.1 billion tonnes of GHG [4].

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2. The Case of the Gulf Countries

The Gulf[1] is the historic heartland of the global O&G sector as it holds almost half of the world's proven hydrocarbon reserves [5] and, in 2022, it produced nearly one-third of the world's oil [6], making the region a critical hub for global energy supplies. The Gulf countries, shown in Figure 1, contribute ~5.2% of global energy-related CO_2 emissions mainly from the burning of fossil fuels for power generation, with natural gas accounting for 56.4%, oil 42.6% and coal 1% [7]. Figure 2 illustrates the proven O&G reserves over the past two decades in this region compared to the rest of the world. Saudi Arabia holds the largest proven oil reserves, accounting for an average annual of 264.12 billion barrels, with the giant Ghawar Field being the world's most productive. Following that, Iran and Iraq, with annual oil reserves averaging 138.27 and 127.75 billion barrels respectively, play crucial roles in the region's energy dynamics despite geopolitical challenges. Kuwait and the United Arab Emirates (UAE) also boast substantial oil reserves contributing to their economies with averages of 100.47 and 97.8 billion barrels per year, respectively. Qatar, although smaller in oil reserves with an average of 20.09 billion barrels per year, is a leading global exporter of liquefied natural gas (LNG). Oman and Bahrain, while possessing smaller reserves compared to their neighbors with annual oil reserves of 5.41 and 0.13 billion barrels respectively, are essential players in regional energy markets. When considering natural gas reserves, Iran leads with an annual average of 1046.42 tcf, followed by Qatar with 799.25. Saudi Arabia and the UAE with significant reserves as well averaging an annual 267.55 and 214.69 tcf, respectively. Iraq holds 115.02 tcf, while Kuwait at 59.62 tcf, Oman 27.47 tcf and Bahrain 3.63 tcf.

Collectively, these countries hold a substantial portion of the world's O&G resources, heavily influencing global energy market and policies. Noteworthy, the O&G sector is characterized by a value chain segmented into upstream, midstream, and downstream operations. Each segment plays a critical role in ensur-

Figure 1: Geographical boundaries of the Gulf countries (Source: Data from Net Zero Tracker [2]).

ing the efficient extraction, transportation, and conversion of O&G into usable products, considering the following main operations and corresponding sub-operations:

Upstream – (1) **Discovery/Exploration:** This initial phase involves seismic surveys, gravity and magnetic surveys, and exploration drilling to locate potential O&G reserves. (2) **Field Development/Drilling:** Once a viable reserve is identified, development drilling begins which includes onshore and offshore drilling and vertical and horizontal drilling, utilizing various rigs such as land-based rigs, offshore rigs, and subsea rigs. (3) **Production/Extraction:** The extraction process begins with primary extraction using the reservoir's inherent pressure, followed by secondary methods like water or gas injection, and tertiary retrieval such as steam injection to maximize recovery.

Midstream – (4) **Processing:** Processing plants and refineries treat and refine O&G to prepare them for further processing. (5) **Transportation:** The transportation of O&G is primarily conducted through pipelines (the most common method), tankers for water transport, and/or trucks for short-distance land transport. (6) **Storage and Trading:** The processed O&G is stored in facilities like tank farms, underground storage, and/or trading hubs where these resources are bought and sold through distribution terminals.

Downstream – (7) **Conversion/Refining/Manufacturing:** O&G are refined into finished products such as gasoline, diesel, jet fuel, petrochemicals, and lubricants. (8) **Sales and Marketing:** Marketing and selling of refined products to wholesalers (industrial or commercial entities), retailers, and end consumers. (9) **Distribution:** The final phase includes the distribution of refined products through pipelines, tankers, and trucks reaching end consumers via gas stations, convenience stores, and other retail outlets.

3. Decarbonization Mechanisms

The O&G industry is now on the cusp of a new era for the decarbonization of the energy system. To accelerate the transition, governments and energy companies of the Gulf countries must harness the full potential of digitalization and energy efficiency in the O&G sector. Digitalization refers to the increasing use of information and communications technology (ICT) across the economy, particularly within energy systems. It involves the convergence of the physical and digital worlds and is composed of three fundamental elements: data, which is the digital information; analytics, which involves using data to gain valuable insights; and connectivity, which refers to the exchange of data between people, machines (including machine-to-machine communication), and devices via communication networks [9]. Digitalization can revolutionize O&G operations and significantly support the shift towards a more sustainable energy landscape across the Gulf countries given the following opportunities:

- —***Environmental:*** Increase the operational efficiency and reliability of relevant processes, Improve equipment longevity, Optimize energy production across the various processes, Mitigate risks through more informed data-driven decisions, Reduce energy consumption and minimize the carbon footprint/emissions of the industry, Enhance exploration accuracy and better manage supply chains.
- —***Economic:*** Better resource and asset management, Increase market competitiveness, Reduce downtime, inspection times, and maintenance costs while ensuring continuous operations, Reduce the

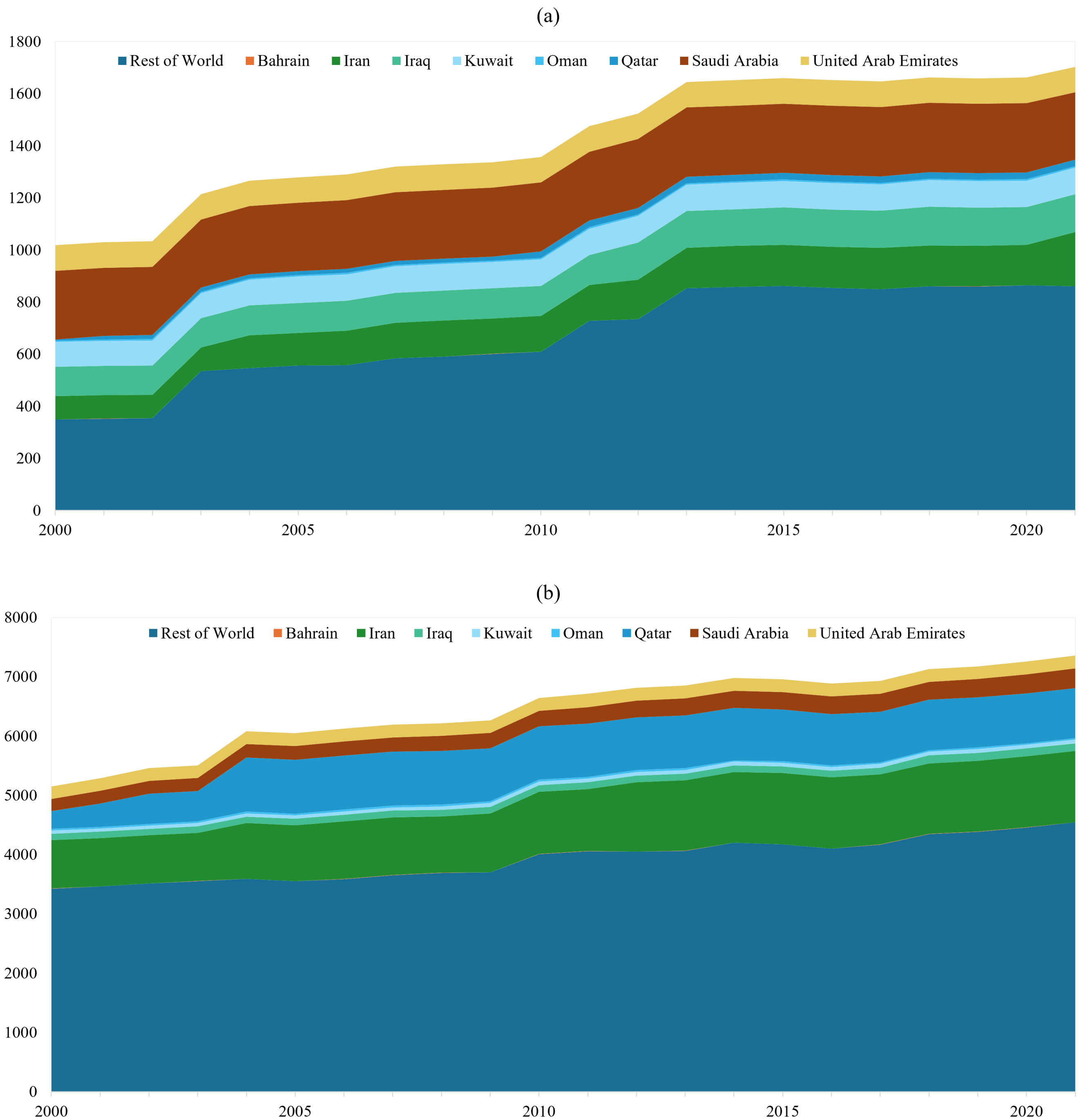

Figure 2: Gulf countries (a) oil reserves in billion barrels (billion b) and (b) natural gas reserves in trillion cubic feet (tcf) (Source: Data from U.S. Energy Information Administration [8]).

impact of price volatility, Evolve business models per global standards and best practices.

—***Social:*** Improve workplace safety by detecting leaks or other anomalies promptly, Provide better experiences for customers and partners, Improve workforce skill and knowledge development.

This section explores the role of different strategies and interventions in facilitating the clean energy transition for the O&G sector by delving into several key areas leveraging advanced technologies.

3.1 Digital Technology

Following the steam engine era of Industry 1.0, the electrification era of Industry 2.0, and the information era of Industry 3.0, Industry 4.0 represents the technological advancements of the 21st century. Also known as the Fourth Industrial Revolution (4IR), Industry 4.0 ushers in an "intelligence era" through the integration of information technologies that blur the boundaries between physical, digital, and biological realms driving profound industrial transformation [10]. These digital

Table 1: Summary of key 4IR technologies for the digital transformation of the O&G sector.

Digital Technology	Description	Reference(s)
Blockchain	Decentralized digital ledger to record transactions across multiple computers securely.	[9][11][12]
Mobile technology	Advanced smartphones and tablets for field data collection, remote monitoring, and real-time communication.	[9]
Digital twin	Virtual replica of physical assets, processes, or systems.	[11][13][14]
Cloud computing	Scalable and flexible storage and computing resources over the internet.	[13][14]
Cognitive computing	Simulate human thought processes using computerized models.	[13]
Edge computing	Data processing near the data generation source rather than in a centralized data-processing warehouse to improve response times and reduce bandwidth usage.	[15]
Internet of Things (IoT) and Industrial Internet of Things (IIoT)	Interconnected sensors and devices that collect and transmit data in real-time.	[9][11][13][14]
Robotics and automation	Automated machines and robots to perform tasks traditionally done by humans.	[9][11][13]
Drones and unmanned vehicles	Autonomous devices used for aerial and subsea inspections, environmental monitoring, data collection, and access to hard-to-reach areas.	[13]
Virtual/Augmented reality and wearable devices	Immersive experiences for training, simulation, and maintenance activities, while providing real-time information and hands-free communication.	[11][14]
3D printing and additive manufacturing	Three-dimensional objects from digital models by adding material layer by layer.	[11][13][14]
Big data analytics	Analyze large volumes of data to uncover patterns, trends, and insights.	[9][11][13][14]
Machine learning and Artificial intelligence (AI)	Mathematical algorithms to analyze data and make predictions or decisions, and computer models to replicate real-world processes and systems.	[13], [14], [16]–[19]
Wireless communication	Transmission of data over wireless networks.	[11]
Quantum computing	Highly complex computations and process information at unprecedented speeds much faster than traditional computers.	[14]
Digital marketing and sales	Online platforms and tools to promote products/services and facilitate transactions.	[9]

solutions are reshaping the global economy, including energy, to enable modern life and meet the world's growing energy demand. Table 1 outlines key 4IR technologies for the digital transformation of the O&G sector to decarbonize the energy system in pursuit of the NZE agenda.

3.2 Renewable Energy

As it is too soon to see a rapid decline in O&G, transformation must also happen in legacy energy assets that we have right now through shifting to renewable energy systems to reduce the industry's carbon footprint [15]. The natural conditions of hydrocarbon fields are highly suitable for integrating new clean energy sources, therefore, renewable energy can be integrated into O&G operations through the following [20]:

—***Solar:*** Solar oil recovery involves using thermal energy from sunlight collected by solar collectors to heat water and produce steam which is then injected into oil formations through injection wells, heating the heavy oil, increasing formation pressure, and forcing the crude oil out through production wells.

—***Wind:*** Wind energy for oil recovery involves installing on-site wind turbines which generate electricity from wind to drive pumps that produce O&G. The offshore industry has energy infrastructure capable of withstanding harsh weather, making it suitable for integrating wind energy.

—***Geothermal:*** Hot water oil recovery uses geothermal resources and water injection technology to transfer large amounts of heat into shallow oil formations by developing fluids (oil, gas, water and their mixtures) at high temperatures in deep layers, which thus reduces the oil viscosities and improves the oil flow capacities.

—***Biofuel:*** Biofuel production technology is a CO_2 recycling technology that decreases CO_2 emissions by reducing the use of oil. Advances in alcohol fuel production using nonfood crops as raw materials have gradually resolved issues related to raw material processing and production costs.

3.3 Alternative Fuels

As a clean fuel, hydrogen has a high combustion calorific value and its combustion byproduct is water meaning it does not emit GHG into the environment. It serves as a versatile energy carrier, capable of being transformed into and from other forms such as electricity, ammonia, methanol, and synthetic fuels, making it a crucial solution for industrial decarbonization where direct electrification is not viable. The strong connection between hydrogen and renewable, low-carbon energy sources promotes its use as an energy vector. Producing hydrogen from fossil fuels offers a transitional pathway from high-emission combustion processes to cleaner, lower-carbon alternatives. One of the most widely used methods is steam methane reforming (SMR), which accounts for nearly 50% of global hydrogen production. Currently, hydrogen production in the refining industry primarily relies on grey hydrogen technology, which uses coal and other fossil fuels. Moving forward, the focus should shift to advancing decarbonization strategies for hydrogen use including blue hydrogen technology which utilizes fossil fuels combined with storage systems, green hydrogen technology which generates electricity from renewable energy and biomass, and low-carbon hydrogen from nuclear energy-generated heat [20][21].

3.4 Carbon Removal

Carbon capture, utilization, and storage (CCUS) involves separating CO_2 from industrial processes, energy use, or the atmosphere, and then using it directly or injecting it into the ground for permanent emissions reduction. Approximately three-quarters of the 40 million tons (Mt) of CO_2 captured annually by large facilities come from O&G operations [20]. Using CCUS processes, CO_2 is captured using various capture systems such as pre-combustion, post-combustion and oxy-fuel combustion, then transported by tanker, ship, or pipeline for utilization or storage [21]. Uses include resource utilization by injecting CO_2 into the ground to increase O&G recovery rates or injecting into deep geological reservoirs for long-term isolation of CO_2 from the atmosphere. The O&G industry has the necessary technical capacity and expertise to handle large volumes of CO_2 and expand CCUS deployment [20]. There are three main processes to which CCUS can be applied to reduce the emissions intensity of O&G operations to help decarbonize the energy system [4]:

—***Gas processing:*** Natural gas extraction often involves removing impurities, including CO_2, which is typically vented into the atmosphere. Around 150 Mt of CO_2 are extracted annually from O&G operations, with 125 Mt being vented. The remaining 25 Mt of CO_2 is mostly used for enhanced oil recovery by injecting it into oil fields, with some being stored in inactive fields.

—***Refining and bitumen upgrading:*** Around 40 Mt of hydrogen are used annually for refining and upgrading oil globally, generating significant CO_2 emissions that can be captured. Hydrogen production units produce a relatively pure stream of CO_2, often vented, accounting for 60% of total CO_2 emissions from steam methane reformers which can be directly captured. Coal- and natural gas-based hydrogen units can be designed for up to 95% CO_2 capture to lower emissions intensity. CCUS can also reduce emissions from catalytic crackers, heat plants, and power generation at refinery sites.

—***Liquefied natural gas:*** Liquefying natural gas requires cooling to -162°C, an energy-intensive process typically powered by consuming a portion of the gas being processed, averaging around 9% of the gas globally. This process, combined with any venting of naturally occurring CO_2, results in the emission of approximately 2-3 tonnes of CO_2 for every ten tonnes of LNG produced. Currently, no projects utilize CCUS to mitigate these emissions, although implementing CCUS can potentially reduce emissions by around 90%.

3.5 Methane Abatement

Methane is the second largest global GHG after CO_2 [20], responsible for around 30% of the rise in global temperatures since the Industrial Revolution where the O&G sector is responsible for 80 Mt of methane emissions, equivalent to 2.4 giga tonnes CO_{2eq} [4]. As part of the Global Methane Pledge, 158 countries (including the Gulf countries except for Iran) representing over 50% of global anthropogenic methane emissions, have committed to work together to collectively reduce methane emissions by at least 30% by 2030 (relative to 2020 levels) [22]. The O&G industry can decrease methane emissions by approximately 75% by using existing technologies and measures, with approximately 40% of that methane achieving net zero cost reductions [20]. Examples include leak detection and repair campaigns, installing emissions control devices (vapor recovery units, blowdown capture, flares, plunger), and early replacement of existing components that emit methane by design (pumps, compressor seal or rod, air systems, electric motor) [4].

3.6 Flaring Control

Around 140 billion cubic meters of natural gas was flared in 2022 resulting in 500 Mt of CO_{2eq} emissions [4]. There are several efforts to cut down on flaring, including the Zero Routine Flaring by 2030, launched by the World Bank and the United Nations in 2015, which commits governments and companies to end routine flaring no later than 2030. Currently, the endorsers of the initiative include 36 governments including Bahrain, Oman, Saudi Arabia and Iraq [23]. There are many options for using natural gas that is currently flared, including bringing it to consumers/market via new pipeline connections or existing gas networks of transmission or distribution grids, reinjecting it to support reservoir pressure, or converting it to compressed natural gas (CNG) or LNG. Except for gas injection, the gas that is saved can be resold significantly lowering the net cost of abatement. New technologies have made it easier to monitor flares on a near real-time basis, helping companies to identify bottlenecks and opportunities in operated and non-operated assets. For example, mobile mini-LNG or CNG production equipment can reduce the need for flaring and venting during well-testing and other short-term operations [4].

4. Selected Real-World Use Cases

As the world's energy system is changing fundamentally, the region's position at the heart of the global O&G sector implies that the impact of the global decarbonization and clean energy transition agenda is likely to be felt more acutely over the coming years. In the wake of the 4IR, governments and national oil companies (NOCs) across the region are beginning to realize the shift globally towards digital and advanced technologies. These technologies, as presented in Section 3, can be integrated into O&G operations through a plethora of applications including monitoring of equipment health/performance, field surveillance, predictive maintenance, tracking environmental conditions, remote asset management, digital prototyping, real-time data collection and analysis, demand forecasting, operational automation and analytics, pricing optimization, logistics route management, and pipeline/refinery

Table 2: Existing or planned projects using digital and advanced technologies in NOCs in the Gulf countries.

Country, Company	Decarbonization Mechanisms	Applications	Reference(s)
United Arab Emirates, ADNOC	Digital Technology	Belbazem offshore block uses AI modelling and analysis tools to analyze reservoir data, manage reservoir operations and optimize production. Panorama Digital Command Center aggregates data from across operations providing real-time insights through smart predictive analytical models, AI, and big data. Hyperledger Fabric-based system for automated accounting and rapid transaction settlement in oil product sales. Digital twin in Taweelah gas compression plant.	[12][14][24][25]
	Carbon Removal	Projects include CO_2 storage hub (planned, 5 $MtCO_2$/year), Habshan-Bab gas plant (under construction, 1.5 $MtCO_2$/year), Hail and Gasha (under construction, 1.5 $MtCO_2$/year), ADNOC ENEOS Mitsui Ruwais Industrial Area (planned, 0.46 $MtCO_2$/year), Oxy/ADNOC Direct Air Capture (planned, 1 $MtCO_2$/year), Shah gas plant (planned, 2.3 $MtCO_2$/year), and TA'ZIZ blue ammonia (planned, 1.7 $MtCO_2$/year).	[26]
Saudi Arabia, Aramco	Digital Technology, Methane Abatement, Flaring Control	Shallow Water Inspection and Monitoring Robot for pipelines inspection in shallow waters. Uthmaniyah gas plant uses advanced analytics and drones to inspect pipelines/machinery. Khurais field uses 40,000 IoT sensors to monitor and forecast the behavior of more than 500 oil wells creating the world's first advanced process control for a conventional field. Abqaiq oil processing facility uses robots and smart drones, machine learning and AI algorithms, data analytics and predictive modeling to boost performance and efficiency. Yanbu oil refinery uses predictive maintenance, advanced data analytics, and automation to optimize processes and reduce downtime. Hasbah field uses digital twin for project design, construction planning, supply chain, materials handling, and facility operations and maintenance. Center AI hub leverages advanced analytics and machine learning solutions including unmanned aerial vehicles for operational uses of air, ground, and underwater robots that support flare stack inspection or methane gas detection, augmented and virtual reality to train operators on the plant experience from a simulation booth, and wearable technologies such as digital glasses and helmets to connect field workers to other employees for real-time interaction and collaboration. Additive manufacturing center that 3D prints a wide range of products for industrial uses. Cloud-based platform solution, eMarketPlace, to optimize supply chain processes. Smart Gas Detector to detect gas using electrochemical sensors using IIoT technology to deliver high-performing self-diagnostics compared to conventional detectors. Camera-Based Well Space Out system with smart high-resolution wireless cameras, and other sensors that use AI and machine learning to process the video and imagery captured to optimize the placement of the drillstring assembly a critical step in the process of drilling new hydrocarbon wells. Big Data Dammam-7, one of the world's most powerful supercomputers provides the vast computational power for running detailed 3D seismic models to recover and discover O&G. Supply Chain Control Center uses AI solutions and advanced analytics for real-time alerts to business disruption, live logistics tracking, and end-to-end visibility on supply chain. In-house reservoir and basin simulator, TeraPOWERS, using big data to simulate the Arabian Peninsula hydrocarbon system by updating models with new drilling and production data and employing algorithms to maximize access to hydrocarbon resources. In-house AI-powered i4Safety 2.0 Hazard & Incident Prediction tool using historical data to predict on-site incidents and hazards to increase safety and efficiency in operations.	[27][28]
	Carbon Removal	Projects include Jubail Hub agreement (planned, 9 $MtCO_2$/year) and Uthmaniyah CO_2 enhanced oil recovery demonstration (operational, 0.8 $MtCO_2$/year).	[26]

(continued)

Table 2: Existing or planned projects using digital and advanced technologies in NOCs in the Gulf countries. *(continued)*

Country, Company	Decarbonization Mechanisms	Applications	Reference(s)
Oman, Petroleum Development Oman	Digital Technology	Digital oil field connecting 2,000 wells where real-time data informs about electric submersible pump performance and auto-generates online well models.	[29]
	Renewable Energy	Miraah, one of the world's largest solar plants, harnesses solar energy to produce steam for oil production. The 330 megawatts solar thermal facility reduces natural gas used to generate steam for thermal enhanced oil recovery by generating an average of 2,000 tons of solar steam daily injected into the oil reservoir to heat the oil making it easier to pump to the surface and facilitating easier extraction at the Amal oilfield.	[30]
Kuwait, Kuwait Oil Company and Kuwait National Petroleum Company	Digital Technology	Sabriyah pilot comprises 49 wells each instrumented with state-of-the-art technology from subsurface to surface to acquire real-time data, upgrade power and communication infrastructure, and create collaborative decision centres to automate work processes.	[31][32]
		Private cloud in two data centres built on digital solutions using automation, big data, and smart applications to virtualize compute, storage, network, and security layers and automate lifecycle management of all software components across the organization's infrastructure.	
Bahrain, Tatweer Petroleum	Digital Technology	Smart technology to monitor the wells with 500,000 IoT sensors fitted across the oil field to ensure that all wells are running as efficiently and safely as possible.	[33][34]
		Collaboration with UAE-based AI technology firm "AIQ" to integrate AI and digital solutions into upstream operations using advanced machine learning and data science to optimize field architecture, improve performance, and reduce operational risks.	
	Renewable Energy	Solar power plant produces 3 megawatts of electricity, supplying around 6% of the company's total energy needs to reduce the use of natural gas for generating electricity and helping in the conservation of natural resources and the protection of the environment. The generated power is fed back into the power grid for use in oil field operations.	[35]
Qatar, QatarEnergy	Carbon Removal	Projects include Qatar LNG (operational, 1.23-2.1 $MtCO_2$/year) and Qatar North Field East Project (under construction, 2.9-4.3 $MtCO_2$/year).	[26]
	Renewable Energy	Al Kharsaah 800 megawatts photovoltaic power project applies the latest solar energy technologies to optimize electricity production and features automated systems for sun-tracking and robotic cleaning of solar panels, supplying 10% of the country's peak energy consumption and diversifying power sources by reducing the reliance on natural gas for power generation.	[36]
Iran, National Iranian Oil Company	Digital Technology	Strategic AI center to digitalize 15 O&G fields along with acquiring technology for drilling long multilateral horizontal wells by using homegrown rotary steerable system.	[37][38]
		A joint venture with Chinese tech companies to employ AI in the whole value chain including exploration, drilling, production and development.	
Iraq, National government and authorities	Renewable Energy	1 gigawatts solar power plant to supply electricity to the Basrah regional grid to enhance the development of natural resources and improve electricity supply, and recover the flared gas on three oil fields to supply gas to power generation plants and the construction of a seawater treatment plant for pressure maintenance to increase regional oil production.	[39]

corrosion monitoring, among various others. Table 2 sheds light on applications of digital and advanced technologies in the Gulf countries showcasing trends that are becoming a key focus for investment as companies prepare for the future.

5. Challenges and Enablers

The above technologies and measures are radically restructuring the O&G sector, creating both opportunities and potential challenges for energy companies which include but are not limited to [9][21][40]:

- —***Lack of Technical Expertise****:* Implementing and maintaining digital technologies necessitate specialized workforce skills, yet there is often a shortage of qualified personnel who can manage and operate advanced systems.
- —***Cybersecurity Risks:*** Increased vulnerability to potential cyberattacks due to interconnected digital devices/systems with multiple access points.
- —***Siloed Systems:*** Drilling, completions, geosciences, production, and reserves systems in most O&G organizations are siloed as these systems are created, managed and stored using various software and databases and by numerous teams within the organization.
- —***Data Handling:*** Implementation of digital technologies generates large volumes of data.

- —***Geological Uncertainty:*** The inherent variability in geological formations presents a significant challenge particularly for technologies such as CCUS.
- —***Capital Intensity:*** High initial investment costs associated with the deployment of new technologies and infrastructure for renewable energy and clean fuels given budget constraints and uncertain economic benefits.
- —***Resource Availability:*** The availability of necessary resources, such as water for hydrogen production or specific materials for renewable energy technologies, can be limited and geographically constrained.
- —***Technological Obsolescence:*** The rapid pace of technological advancements can make new systems and tools obsolete quickly, necessitating continuous updates and investments.
- —***Technological Maturity:*** Some clean technologies, like advanced biofuels and hydrogen, are still in the early stages of development and deployment and thus their commercial viability and scalability remain uncertain.
- —***Ambient Settings:*** Deploying digital technologies in extremely high temperature and pressure environments of O&G operations impacts durability and accuracy, especially in hot climates typical of many oil-producing regions or environmentally sensitive or dangerous areas such as deserts and areas affected by war.
- —***Market Dynamics:*** Adapting to changing market demands and competition from alternative energy sources while navigating complex regulatory frameworks.
- —***Intellectual Property (IP) Forge and Contractual Risks:*** Implementing digital technologies involves complex IP and contractual challenges including protecting proprietary technologies, negotiating clear and fair contracts, and managing IP rights across stakeholders which can lead to disputes over ownership, licensing agreements, and data sharing, ultimately hindering collaboration and slowing digital transformation.

To successfully navigate potential challenges in transforming the O&G sector for the Gulf countries, NOCs must focus on key enablers which refer to "critical success factors" that present key areas in a business where positive results are crucial to ensure successful competitive advantage, and if results fall short, the organization's overall performance will suffer [41]. Suggestions to accelerate the clean energy transition of the O&G sector include [9][21][29][40][41]:

- —***Workforce Development:*** Invest in training and awareness education to build a skilled workforce capable of handling new energy systems and digital technologies while adhering to safety measures from high-risk activities and hazardous materials through the use of personal protective equipment, the implementation of safety procedures, and the monitoring of equipment and processes.
- —***Operational Resilience:*** Implement robust cybersecurity protocols and measures to protect computer systems, digital infrastructure, and connected networks from cyber threats.
- —***System Integration:*** Ensure compatibility of new technologies with existing operations and legacy infrastructure to function as a coordinated whole through careful planning and retrofitting where needed to avoid systems interference and potential disruptions.
- —***Data Management:*** Robust computing infrastructure and sophisticated algorithms are required to manage, store, and process data securely and efficiently.
- —***Geotechnical Stability:*** Detailed geological surveys and continuous monitoring to understand the geological characteristics of storage sites and ensure the long-term integrity of carbon storage over extended periods.
- —***Innovative Financing***: Explore financing mechanisms and incentives, such as green bonds, carbon trading tax breaks or subsidies, to fund energy transition projects while considering return on investment (ROI).
- —***Stakeholder Cooperation:*** Foster public-private collaboration between government, industry, and academia to accelerate the deployment of new technologies and access to critical resources and raw materials residing in particular geographical regions.
- —***Technological Adaptability:*** Establish partnerships with technology vendors and startups to gain early access to emerging technologies and invest in modular and scalable digital infrastructure that can be incrementally updated without significant disruptions to operations.
- —***Pilot and Scale:*** Allocate funding for research and development (R&D) to accelerate the development of clean technologies with pilot demonstrations for performance data and viability assessment before full-scale deployment, and facilitate technology transfer from international partners to advance local capabilities.
- —***Environmental Control:*** Conduct thorough testing and validation in simulated environments, implement regular calibration and maintenance protocols to guarantee the reliability of technology in extreme conditions and use high-quality durable materials and coatings for digital equipment for resistance to corrosion and wear.
- —***Effective Governance:*** Align with international standards and best practices for O&G operations that encourage innovation and investment in digital technologies and clean energy.
- —***IP and Contract Management Systems:*** Develop clear IP policies, ensure detailed and transparent contracts for new technologies, and create collaborative frameworks with predefined dispute resolution mechanisms. Engage legal experts and use advanced contract management software to streamline processes and maintain compliance.

In closure, we argue that a rapid and significant change in the pace and scale of industry actions is imperative to achieve the necessary transition. Government leaders and responsible corporations need to prioritize decarbonization strategies to make NZE a reality. The O&G sector is facing growing public concern over climate change, stricter government regulations, and a volatile global energy market. The ongoing drive to reduce emissions and the environmental damage caused by the energy industry will require innovative solutions from O&G companies that wish to flourish in this era of change. Enterprises may leverage free cash flow from resilient O&G assets to drive digital transformations and clean energy transitions. Management support and strong leadership are vital to fostering a cultural shift within organizations for commitment to a smooth transformation. Uncertainties remain about the future of the energy system, but those preparing today to meet anticipated demand trends and adopt appropriate technologies will fare better than those who neglect the need for change or investment in future-proof technologies. The strategic choices, policies, and plans made today by governments and operators in the region are likely to prove to be fundamental to their success or failure within the energy system in the coming decades to meet the objectives set forth by global climate agendas.

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Footnotes

[1] While it is referred to as the Persian Gulf in Iran, the Arab governments refer to it as the “Arabian Gulf” or the “Gulf”. In this article, the Gulf is used.