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Renewable energy integration in offshore oil and gas installations

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Abstract

As the oil and gas industry seeks to reduce its carbon footprint and align with global decarbonization goals, integrating renewable energy sources into offshore operations presents a promising pathway. This review examines the feasibility of incorporating renewable energy technologies such as offshore wind, solar, and marine energy into the power supply of oil and gas installations. Offshore wind energy, with its high potential and scalability, emerges as a viable option for powering rigs, as demonstrated by projects like Hywind Tampen in Norway, which uses floating wind turbines to supply energy to oil platforms. Solar energy, while more limited in offshore environments due to space and weather constraints, can be part of hybrid systems combining multiple renewable sources. Marine energy, including tidal and wave power, is still in its developmental stages but holds promise for future applications. The review explores hybrid energy systems that integrate renewable sources with conventional energy, such as gas turbines, to ensure continuous power supply. Microgrid technologies and energy storage solutions are also discussed as essential components for balancing renewable energy's intermittency and optimizing power distribution. Key challenges, such as the harsh marine environment, high initial investment, and the need for new infrastructure, are analyzed alongside potential solutions like technological innovations in floating renewable systems and automated monitoring technologies. Economic feasibility is considered through a cost-benefit analysis, highlighting the potential long-term savings from reduced fuel use and the benefits of regulatory incentives for renewable energy integration. Ultimately, the integration of renewables not only supports decarbonization but also offers operational efficiency and cost reduction opportunities. This review concludes by examining future trends in renewable energy for offshore installations and the potential for fully electrified, sustainable oil and gas platforms.

Keywords: Renewable Energy; Offshore Oil; Gas Installations; Review

1. Introduction

The global imperative to address climate change has catalyzed a significant shift in energy production and consumption, with a primary focus on decarbonization (Papadis and Tsatsaronis, 2020). The oil and gas sector, a major contributor to greenhouse gas emissions, plays a crucial role in this transition. As countries strive to meet ambitious carbon reduction targets, the integration of renewable energy sources into traditional fossil fuel operations has become increasingly vital (Abbasi *et al*., 2022). This introduction outlines the importance of reducing emissions in the oil and gas industry, examines the feasibility of renewable energy integration in offshore oil and gas installations, and presents the objectives of this review, which explores the potential and challenges of using renewable energy to power oil platforms.

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The urgency to reduce emissions in the oil and gas sector stems from its substantial contribution to global carbon emissions (Hastings and Smith, 2020). According to the International Energy Agency (IEA), the oil and gas industry accounted for approximately 42% of global CO2 emissions from fuel combustion in 2020. As governments and organizations worldwide commit to achieving net-zero emissions by mid-century, the oil and gas sector faces mounting pressure to reduce its carbon footprint (Friedmann *et al*., 2020). This necessity underscores the importance of adopting innovative strategies and technologies that facilitate the transition to a low-carbon future. Renewable energy sources, such as wind, solar, and biomass, have emerged as promising solutions to mitigate emissions associated with fossil fuel extraction and processing (Igogo *et al*., 2021). Their potential to displace conventional energy sources in oil and gas operations is significant, particularly as the industry seeks to improve its sustainability profile. Integrating renewable energy into oil and gas operations not only helps in reducing emissions but also enhances energy security, diversifies energy portfolios, and may lead to long-term cost savings (Cherepovitsyn *et al*., 2023).

The feasibility of integrating renewable energy into offshore oil and gas installations is increasingly recognized as a viable strategy for enhancing operational efficiency and reducing environmental impact (Zou *et al*., 2021; Al-Shetwi, 2022). Offshore platforms, which traditionally rely on diesel generators for power, have a unique opportunity to harness abundant renewable resources available in marine environments. For instance, offshore wind energy has gained momentum, with several countries investing in large-scale wind farms near coastlines. These installations can generate substantial amounts of electricity, which can be used to power drilling operations, processing facilities, and other ancillary services on oil platforms (Vidal *et al*., 2022). Moreover, the implementation of hybrid energy systems that combine fossil fuels with renewable energy sources can optimize energy efficiency while lowering emissions. By integrating renewable energy, oil companies can reduce their dependency on conventional power sources, enhance the reliability of energy supply, and minimize operational costs associated with fuel transportation and consumption (Oyekale *et al*., 2020).

This aims to explore the potential and challenges of using renewable energy to power oil platforms, particularly in offshore and remote environments. Specifically, the objectives are threefold. Assessing the potential of renewable energy Integration. This involves evaluating the feasibility of various renewable energy sources, including wind, solar, and wave energy, for powering oil rigs. The analysis will consider technological advancements, environmental conditions, and operational requirements. While the integration of renewable energy presents numerous opportunities, it also poses significant challenges. This review will investigate the technical, economic, and regulatory barriers that hinder the widespread adoption of renewable energy in offshore oil and gas operations. Based on the assessment of potential and challenges, the review will provide recommendations for industry stakeholders on best practices and strategies for successfully integrating renewable energy into existing and future oil platforms. These recommendations will emphasize collaboration between government, industry, and research institutions to facilitate innovation and investment in renewable technologies.

As the oil and gas sector navigates the complexities of decarbonization, the integration of renewable energy sources emerges as a crucial strategy for reducing emissions and enhancing sustainability (Ghorbani *et al*., 2023). This review seeks to contribute to the understanding of the potential and challenges associated with renewable energy integration in offshore oil and gas installations. By examining the current landscape and identifying pathways for successful implementation, this research aims to support the industry in its efforts to transition toward a more sustainable and low-carbon future.

2. Energy Demands of Offshore Oil and Gas Installations

Offshore oil and gas installations play a pivotal role in meeting the world's energy demands, but they are also among the most energy-intensive operations in the industry (Abdulrahman *et al*., 2021). Understanding the energy demands of these installations is crucial for identifying opportunities for efficiency improvements and sustainable practices. This examines the current energy use on offshore rigs, including energy-intensive processes and sources, and explores the environmental and economic impacts of current energy consumption.

Offshore oil and gas operations involve a range of energy-intensive processes, including drilling, production, and compression (Chen *et al*., 2023). The drilling process requires substantial energy to penetrate geological formations. Rotary drilling rigs, equipped with high-capacity drill bits and heavy drilling equipment, consume considerable amounts of energy. This energy is primarily used to power the drill string, mud pumps, and other auxiliary systems necessary for well construction. The drilling phase can last several weeks to months, leading to significant energy consumption. Once a well is drilled, the production phase begins, which involves extracting crude oil or natural gas from the reservoir. This process requires energy for various tasks, including pumping fluids to the surface, separating oil, gas, and water, and transporting these products to processing facilities. Production platforms often use high-capacity compressors and pumps that consume large amounts of energy to ensure efficient recovery of hydrocarbons (Zichittella and Pérez-Ramírez, 2021). Compression is critical for transporting natural gas through pipelines. Offshore installations often use gas turbines or reciprocating compressors, both of which are energy-intensive. Compressors must maintain high pressure levels to facilitate the flow of gas, particularly over long distances. The energy demands for compression can be substantial, contributing significantly to the overall energy consumption of offshore operations. The energy used in offshore oil and gas operations primarily comes from fossil fuels, with diesel and gas turbines being the predominant sources. Diesel generators are commonly employed on offshore platforms to provide power for drilling and production activities (Zhang *et al*., 2021). Diesel is favored for its availability, high energy density, and reliability. However, reliance on diesel also results in considerable greenhouse gas emissions and air pollutants, including nitrogen oxides (NOx) and particulate matter. Gas turbines are often utilized for larger-scale energy needs, particularly for compression and power generation. While they can provide substantial power output, gas turbines are also energy-intensive and contribute to emissions. The combustion of natural gas in these turbines produces carbon dioxide (CO2) and other pollutants, albeit at lower levels than diesel.

The current energy consumption patterns in offshore oil and gas installations have significant environmental and economic implications (Tan *et al*., 2021). The environmental impact of energy consumption in offshore oil and gas operations is substantial. According to the International Energy Agency (IEA), the oil and gas sector is responsible for approximately 40% of global CO2 emissions from fuel combustion. Offshore installations contribute to this figure through various emissions pathways. The combustion of fossil fuels in diesel generators and gas turbines generates direct emissions of CO2, NOx, and other pollutants. Offshore operations can release significant volumes of greenhouse gases, exacerbating climate change. In addition to CO2 emissions, offshore oil and gas operations also produce methane emissions, a potent greenhouse gas. Methane can escape during drilling, production, and transportation processes, contributing to the overall environmental footprint of offshore activities. The emissions from offshore operations can impact marine ecosystems. Increased levels of pollutants in ocean waters can affect marine life, leading to long-term ecological consequences (Zhou *et al*., 2022). The cumulative effect of emissions from multiple installations can degrade water quality and harm sensitive habitats.

The economic implications of current energy consumption in offshore oil and gas operations are equally significant. Reliance on conventional energy sources, particularly diesel and gas turbines, results in high operating costs. Diesel and natural gas prices fluctuate based on market conditions, impacting the overall operational costs of offshore installations (Braga *et al*., 2022). The volatility in fuel prices can lead to unpredictable expenses, complicating financial planning for operators. Energy-intensive equipment such as diesel generators and gas turbines requires regular maintenance and servicing to ensure efficient operation. High wear and tear on machinery due to continuous operation can lead to increased maintenance costs and operational downtime. As environmental regulations tighten, offshore operators may face additional costs associated with compliance. This includes investments in emissions reduction technologies and reporting requirements, further impacting the overall economics of offshore operations. Offshore oil and gas installations have significant energy demands driven by energy-intensive processes such as drilling, production, and compression. The reliance on fossil fuels, particularly diesel and gas turbines, not only results in substantial greenhouse gas emissions but also incurs high operating costs. As the industry faces increasing scrutiny regarding its environmental impact and the urgent need for decarbonization, exploring alternative energy sources and improving energy efficiency will be critical (Habert *et al*., 2020). Transitioning to more sustainable energy practices in offshore oil and gas operations can not only mitigate environmental impacts but also enhance economic viability in an increasingly competitive energy landscape.

2.1. Renewable Energy Sources for Offshore Installations

The transition towards renewable energy sources in offshore oil and gas installations is critical for achieving sustainability and reducing greenhouse gas emissions. As the energy sector grapples with the dual challenges of meeting global energy demands and addressing climate change, integrating renewables such as wind, solar, and marine energy into offshore operations has gained traction (Jegede and Adejonwo, 2023, Agupugo et al., 2022). This explores the potential of various renewable energy sources for offshore installations, emphasizing wind energy, solar energy, and marine energy.

Offshore wind energy has emerged as a viable solution for supplementing the energy needs of offshore oil and gas platforms. The deployment of wind turbines in proximity to oil rigs allows for the generation of clean electricity, reducing reliance on fossil fuels. By harnessing the strong and consistent winds prevalent over the ocean, offshore wind farms can produce significant amounts of energy, which can be used to power drilling operations, production activities, and other energy-intensive processes (Barooni *et al*., 2022). One of the primary advantages of offshore wind energy is its high wind potential. Offshore locations often experience stronger and more reliable winds than onshore sites, making them ideal for wind energy generation. Furthermore, offshore wind farms can be scaled up to meet the energy demands of various operations, with larger turbines capable of generating more electricity. This scalability ensures that as energy requirements increase, additional capacity can be integrated into existing operations without extensive infrastructure changes. A notable example of offshore wind energy integration is the Hywind Tampen project in Norway. This groundbreaking initiative combines floating wind turbine technology with existing oil and gas operations. The project consists of eleven floating wind turbines that supply renewable electricity to two oil and gas platforms in the North Sea. By generating clean energy, Hywind Tampen significantly reduces carbon emissions associated with conventional energy sources while enhancing the overall sustainability of offshore operations (McLaurin *et al*., 2021).

Solar energy is another promising renewable source for offshore installations. Photovoltaic (PV) systems can be deployed on offshore platforms to harness sunlight and convert it into electricity (Huang *et al*., 2023). Solar panels can be installed on the roofs of platforms or integrated into other structures, providing a supplementary energy source to support operations. While the potential for solar energy in offshore environments is substantial, several feasibility and environmental limitations must be considered. Space constraints on platforms can limit the installation of PV systems, particularly on smaller rigs. Additionally, harsh marine conditions, including saltwater exposure and high winds, can impact the durability and maintenance requirements of solar panels. As a result, careful planning and engineering are essential to ensure the reliability and longevity of offshore solar installations. To maximize energy generation and reliability, hybrid systems that combine solar energy with other renewable sources or conventional energy systems are increasingly being explored. For example, integrating solar PV systems with wind turbines can enhance overall energy output and provide a more stable energy supply, particularly in regions with variable weather conditions. Such hybrid approaches not only reduce reliance on fossil fuels but also improve the resilience of offshore installations against energy supply fluctuations (Yuan *et al*., 2020).

Marine energy, derived from tidal and wave movements, presents another opportunity for offshore installations to harness renewable energy. Tidal energy exploits the gravitational pull of the moon and sun, creating predictable tidal currents that can be converted into electricity using turbines (Neill *et al*., 2021). Wave energy, on the other hand, captures the energy generated by surface waves on the ocean. Recent advancements in marine energy technology have led to the development of innovative solutions for capturing tidal and wave energy. Numerous pilot projects worldwide are testing the feasibility of marine energy systems for offshore applications. For instance, the MeyGen project in Scotland is one of the largest tidal energy projects globally, demonstrating the potential for harnessing tidal currents to produce clean energy. Such projects pave the way for broader implementation of marine energy technologies in offshore environments. Despite its potential, harnessing marine energy presents several challenges. The high costs associated with the development and installation of marine energy infrastructure can be a significant barrier to widespread adoption. Additionally, the harsh marine environment poses technical challenges for the durability and maintenance of marine energy systems. Addressing these challenges will require continued investment in research and development, as well as collaboration between industry stakeholders and policymakers. The integration of renewable energy sources such as wind, solar, and marine energy into offshore installations presents significant opportunities for reducing greenhouse gas emissions and enhancing sustainability in the oil and gas sector. The deployment of offshore wind turbines, the use of photovoltaic systems, and the exploration of marine energy technologies are all promising avenues for achieving cleaner energy solutions. However, addressing the feasibility, infrastructure, and cost challenges associated with these renewables will be critical for realizing their full potential in offshore operations. As the energy landscape evolves, the adoption of renewable energy sources will be essential for the future resilience and sustainability of offshore oil and gas installations (Soukissian *et al*., 2023).

2.2. Hybrid Energy Systems and Microgrids

Hybrid energy systems that integrate renewable energy sources with conventional energy generation methods are emerging as essential solutions for enhancing energy efficiency and sustainability, particularly in offshore oil and gas operations (Riboldi *et al*., 2020). These systems combine the reliability of traditional energy sources, such as gas turbines, with the environmental benefits of renewables like wind, solar, and marine energy.

Hybrid energy systems leverage the strengths of both renewable and conventional energy sources to provide a more resilient and efficient energy supply. In offshore settings, gas turbines, often powered by natural gas, can be integrated with renewable sources like wind and solar power. The gas turbines serve as a reliable backup when renewable sources are insufficient, ensuring a continuous and stable energy supply even during periods of low renewable generation. The primary advantage of hybrid systems is their ability to provide continuous energy supply while minimizing carbon emissions. By offsetting a portion of conventional energy use with renewables, these systems reduce reliance on fossil fuels, thereby lowering greenhouse gas emissions and operational costs. Furthermore, hybrid systems can enhance energy resilience, as they are capable of adjusting output based on real-time energy demand and renewable availability

(Amir *et al*., 2022). This flexibility is particularly crucial in offshore oil and gas operations, where energy demands can fluctuate rapidly due to varying operational requirements. Microgrid technology plays a pivotal role in the management of energy within hybrid systems, especially on offshore rigs. A microgrid is a localized energy system that can operate independently or in conjunction with the main power grid (Agupugo et al). By incorporating advanced control systems, microgrids can optimize energy distribution and consumption, balancing the generation from renewable sources with the demand from conventional generators (Muhtadi *et al*., 2021). This capability allows offshore platforms to enhance operational efficiency, reduce energy costs, and improve reliability in energy supply.

Several offshore projects worldwide have successfully implemented hybrid energy systems, demonstrating their viability and effectiveness. One prominent example is the Hywind Scotland project, which integrates floating wind turbines with a gas turbine generator. This project not only harnesses the high wind potential of offshore environments but also ensures a stable power supply during periods of low wind. By utilizing a hybrid system, Hywind Scotland significantly reduces emissions while maintaining operational efficiency (Coles *et al*., 2021). Another notable example is the DONG Energy project in the North Sea, which combines offshore wind farms with gas turbines on oil platforms. The integration of these technologies allows for the effective use of wind energy while providing a reliable backup power source. This project illustrates the potential for hybrid systems to enhance sustainability in the oil and gas sector while ensuring continuous energy availability. Additionally, the Triton Knoll Offshore Wind Farm in the United Kingdom is a case in point where hybrid systems have been adopted. This project combines the energy generated from offshore wind with traditional gas generation to meet the energy demands of surrounding areas. By leveraging hybrid technology, Triton Knoll enhances the overall efficiency of energy production and contributes to the UK's renewable energy targets (Gispert *et al*., 2022).

Hybrid energy systems that integrate renewable energy sources with conventional energy generation offer significant benefits for offshore oil and gas operations. By combining the reliability of gas turbines with the sustainability of renewables, these systems ensure continuous energy supply while reducing carbon emissions. The implementation of microgrid technology further enhances energy management, allowing for real-time optimization of energy distribution (Shotorbani *et al*., 2021). Successful case studies from global offshore projects demonstrate the effectiveness and viability of hybrid systems, paving the way for a more sustainable and efficient energy future in the oil and gas sector. As the industry continues to evolve, the adoption of hybrid energy systems will play a critical role in achieving operational efficiency and environmental sustainability.

2.3. Infrastructure and Technical Challenges

The deployment of renewable energy sources offshore presents unique infrastructure and technical challenges that must be addressed to realize their full potential. As the oil and gas sector increasingly seeks to integrate renewable energy into their operations, understanding these challenges is crucial for successful implementation (Hartmann *et al*., 2021). This examines the key infrastructure requirements for renewable energy systems, the impacts of the harsh marine environment, energy storage solutions, and the technological advancements that offer solutions to these challenges.

The successful deployment of renewable energy systems offshore necessitates robust infrastructure capable of supporting installation and ongoing maintenance. Offshore wind farms, solar arrays, and marine energy systems require specialized vessels and equipment for installation, which can significantly increase project costs (Jiang, 2021). For instance, the installation of offshore wind turbines involves complex logistics, including the transport of large components and the use of specialized lifting equipment. Similarly, solar panels installed on offshore platforms must be designed to withstand harsh marine conditions, necessitating rigorous engineering standards to ensure reliability. The marine environment poses significant challenges to the integrity and durability of renewable energy infrastructure. Factors such as high winds, saltwater corrosion, and severe wave action can accelerate wear and tear on equipment, necessitating frequent inspections and maintenance. This reality not only increases operational costs but also raises concerns about the long-term viability of offshore renewable energy projects. For instance, corrosion-resistant materials and protective coatings are essential for ensuring the longevity of wind turbine components and solar panels, but these solutions can be costly and technically complex. Another critical challenge in deploying renewable energy offshore is the intermittent nature of energy generation. Wind and solar energy production can fluctuate significantly based on weather conditions, necessitating reliable energy storage solutions to balance supply and demand (Abualigah *et al*., 2022). Current technologies, such as batteries and pumped hydro storage, offer potential solutions; however, the logistics of installing and maintaining these systems offshore remain complex. The development of cost-effective, high-capacity energy storage solutions will be crucial for ensuring a stable and reliable energy supply from offshore renewable sources.

Recent advancements in offshore energy technologies offer promising solutions to the challenges faced in deploying renewable energy systems (Hassan *et al*., 2023). For example, floating wind turbines represent a significant innovation, allowing for the installation of wind farms in deeper waters where traditional fixed-bottom turbines may not be feasible. These floating platforms can access stronger and more consistent winds, significantly enhancing energy generation potential. Similarly, the development of deep-sea solar panels, designed to operate in offshore conditions, has the potential to harness solar energy in marine environments effectively. The integration of automation and artificial intelligence (AI) into offshore renewable energy systems can further enhance their efficiency and reliability. Advanced monitoring systems powered by AI can optimize energy generation by analyzing real-time data on weather conditions, energy demand, and system performance. This capability enables proactive maintenance and operational adjustments, reducing downtime and increasing overall energy production. For instance, AI-driven predictive maintenance can identify potential issues before they escalate, allowing for timely interventions that minimize disruptions in energy supply. While the deployment of renewable energy offshore presents significant infrastructure and technical challenges, advances in technology and innovative solutions are paving the way for more effective integration of renewables in the oil and gas sector. By addressing the complexities of installation and maintenance, the impacts of the harsh marine environment, and the need for reliable energy storage, the industry can leverage the potential of renewable energy to enhance sustainability and operational efficiency (Kazimierczuk *et al*., 2023). As technological advancements continue to emerge, the future of offshore renewable energy looks increasingly promising, offering a pathway toward a more sustainable energy landscape.

2.4. Economic Feasibility of Renewable Energy Integration

The economic feasibility of integrating renewable energy sources into oil and gas operations is a critical consideration for companies seeking to balance profitability with sustainability (Hunt *et al*., 2022). This review explores the cost-benefit analysis of renewable energy integration, focusing on initial investments and long-term savings, as well as the financial incentives and support mechanisms that can facilitate the transition to renewable energy.

One of the primary barriers to adopting renewable energy sources in oil and gas operations is the initial capital investment required for infrastructure development (Al-Sarihi and Mansouri, 2022). The cost of installing renewable technologies, such as wind turbines, solar panels, or marine energy systems, can be significant. However, this initial expenditure must be weighed against the potential long-term savings resulting from reduced fuel costs. Renewable energy sources, once established, typically have lower operational costs compared to fossil fuels. For instance, the cost of wind and solar energy has decreased dramatically over the past decade, making them increasingly competitive with conventional energy sources. According to the International Renewable Energy Agency (IRENA), the global average cost of electricity from solar photovoltaics fell by 89% between 2010 and 2020, while onshore wind energy costs dropped by 70% during the same period. As such, companies that invest in renewable energy can benefit from substantial savings in fuel expenditures over time, enhancing overall economic viability. When comparing the costs of renewable energy and conventional sources, it is essential to consider the entire lifecycle of energy production (Ji and Wang, 2021). While the upfront costs for renewable energy technologies may be higher, the ongoing expenses associated with fossil fuels, including extraction, transportation, and emissions-related costs, can be substantial. The external costs of fossil fuels, such as greenhouse gas emissions and environmental degradation, are increasingly being accounted for in economic analyses. This shift has led to a growing recognition of the financial advantages of transitioning to renewable energy sources, particularly as regulatory pressures to reduce emissions intensify. Additionally, the volatility of fossil fuel prices poses a risk to long-term financial planning for oil and gas companies, making the stability offered by renewables an attractive alternative (Considine *et al*., 2023).

To facilitate the integration of renewable energy into oil and gas operations, many governments have introduced policies and financial incentives (Qadir *et al*., 2021). These initiatives include tax credits, grants, and subsidies aimed at reducing the financial burden of initial investments in renewable technologies. For example, in the United States, the Investment Tax Credit (ITC) allows businesses to deduct a significant percentage of the installation costs of solar energy systems from their federal taxes. Such incentives can significantly improve the return on investment (ROI) for companies considering renewable energy projects, making them more economically feasible. Public-private partnerships (PPPs) play a vital role in driving investment in renewable energy by combining the resources and expertise of both sectors. These collaborations can lead to innovative financing solutions and share the risks associated with large-scale renewable energy projects. For example, partnerships between oil and gas companies and renewable energy developers can facilitate the sharing of technology and knowledge, leading to more efficient and effective integration of renewables into existing operations. By leveraging public support and private investment, these partnerships can help create a more favorable economic environment for renewable energy integration (Tzankova, 2020). The economic feasibility of integrating renewable energy into oil and gas operations is increasingly supported by favorable cost-benefit analyses and financial incentives. While initial investments may be substantial, the long-term savings from reduced fuel costs and the stability offered by renewable energy sources present compelling arguments for transitioning to a more sustainable energy model. Government policies and public-private partnerships further enhance the financial viability of renewable energy projects, paving the way for a more sustainable and economically viable future in the oil and gas industry. As the industry continues to evolve, the economic case for renewable energy integration will likely strengthen, contributing to the broader goal of achieving sustainable energy solutions (Breyer *et al*., 2022).

2.5. Regulatory and Environmental Considerations

As the oil and gas industry grapples with the pressing need to mitigate climate change, regulatory and environmental considerations surrounding the integration of renewable energy sources have become increasingly important (Blazquez *et al*., 2020). This explores the environmental benefits of renewable energy use, focusing on reductions in CO2 emissions and the positive impacts on marine ecosystems, as well as the regulatory frameworks that support this transition.

The transition to renewable energy is critical for achieving global decarbonization goals. Fossil fuel combustion is the largest single source of greenhouse gas emissions, particularly carbon dioxide (CO2), which significantly contributes to climate change. By incorporating renewable energy sources, such as wind, solar, and marine energy, oil and gas operations can drastically reduce their carbon footprints (Temizel *et al*., 2023). For instance, a review published in Nature Climate Change indicates that shifting to renewable energy can reduce CO2 emissions from energy production by up to 70% by 2050. This shift not only supports individual company sustainability initiatives but also aligns with national and international climate targets, such as those outlined in the Paris Agreement. By committing to renewable energy, oil and gas companies can play a pivotal role in the global effort to limit temperature rise to well below 2 degrees Celsius. In addition to reducing greenhouse gas emissions, the deployment of renewable energy technologies can positively impact marine ecosystems. Traditional oil and gas operations often generate significant underwater noise and emissions, which can harm marine life and disrupt ecosystems (Ogolo *et al*., 2022). For example, drilling and seismic activities can negatively affect fish populations and marine mammals, such as whales and dolphins. Conversely, offshore renewable energy installations, such as wind farms, have been shown to have a neutral or even positive effect on local marine ecosystems. By reducing reliance on fossil fuels and minimizing emissions, these projects can help improve water quality and enhance biodiversity. Furthermore, the presence of artificial structures, such as wind turbines, can provide new habitats for marine species, potentially leading to increased biodiversity in the region.

To facilitate the transition to renewable energy, various regulatory frameworks have been established at both the international and regional levels. These regulations aim to promote the adoption of renewable energy technologies in oil and gas operations while ensuring environmental protection (Hartmann *et al*., 2021). For instance, the European Union's Renewable Energy Directive sets binding targets for member states to increase the share of renewable energy in their energy mix, thereby incentivizing oil and gas companies to invest in cleaner energy sources. Similarly, the U.S. federal government has introduced policies, such as the Clean Power Plan, aimed at reducing carbon emissions from power generation, which indirectly encourages the oil and gas sector to explore renewable options. Compliance with emissions reduction targets is a critical aspect of the regulatory landscape affecting the oil and gas industry. The Paris Agreement requires participating countries to establish and communicate their nationally determined contributions (NDCs) aimed at reducing greenhouse gas emissions. As countries strive to meet these commitments, they increasingly look to the oil and gas sector to contribute to emissions reductions through renewable energy integration (Praveen *et al*., 2020). Companies that fail to adapt to these regulatory pressures may face financial penalties, reputational risks, and reduced market competitiveness. Therefore, aligning corporate strategies with international climate agreements is not only essential for environmental stewardship but also crucial for long-term business sustainability.

The regulatory and environmental considerations surrounding the integration of renewable energy in the oil and gas industry are multifaceted and critical for the sector's future. The environmental benefits of renewable energy, including significant reductions in CO2 emissions and positive impacts on marine ecosystems, underscore the importance of this transition (Zhou *et al*., 2023). Furthermore, supportive regulatory frameworks at both international and regional levels are essential for driving the adoption of renewable energy technologies. As the industry evolves, compliance with emissions reduction targets and climate agreements will be vital for ensuring a sustainable and environmentally responsible future for oil and gas operations.

2.6. Long-Term Potential and Future Trends

As the oil and gas industry faces increasing pressure to decarbonize and transition toward sustainable practices, the long-term potential and future trends in renewable energy integration present promising opportunities (Arent *et al*., 2022). This discusses the potential for scaling up renewable energy use, emerging technologies that support this transition, and the decarbonization of the entire offshore supply chain.

One of the most significant opportunities for renewable energy integration in offshore oil and gas operations is the potential for full electrification of platforms. Transitioning to an all-electric system powered by renewable energy sources, such as wind and solar, can drastically reduce greenhouse gas emissions associated with traditional fossil fuel-based operations (Satymov *et al*., 2021). For instance, electrification can eliminate the need for diesel generators, which are commonly used on offshore platforms, leading to a substantial decrease in CO2 emissions. Furthermore, the integration of renewable energy technologies can enhance operational efficiency and reliability. As battery storage technologies advance, the feasibility of using renewables for continuous power supply increases, enabling offshore platforms to operate independently from fossil fuels. The development of floating renewable energy platforms represents another promising trend for offshore operations. Floating wind turbines and solar farms can be deployed in deeper waters, where wind and solar resources are typically stronger and more consistent. These innovations not only expand the geographic footprint for renewable energy generation but also minimize visual and environmental impacts associated with fixed structures. Additionally, advancements in energy storage solutions, such as lithium-ion batteries and other emerging technologies, are crucial for balancing supply and demand, ensuring a reliable energy source for offshore operations. Effective energy storage systems can mitigate intermittency issues associated with renewable energy sources, allowing platforms to utilize stored energy during periods of low generation (Datta *et al*., 2021).

The future of renewable energy in offshore oil and gas operations will also be shaped by innovations in marine energy harvesting, such as tidal and wave energy. These technologies harness the kinetic and potential energy of ocean currents and waves, providing a reliable and consistent energy source. Integrating marine energy into offshore platforms can diversify the energy mix, further enhancing sustainability. Additionally, improvements in offshore grid connections will facilitate the transfer of renewable energy between platforms and onshore facilities, creating a more interconnected and resilient energy system. Artificial intelligence (AI) and digital twin technologies are poised to revolutionize the management and optimization of renewable energy use in offshore operations. AI can analyze vast amounts of data to optimize energy consumption, predict maintenance needs, and enhance operational efficiency. Digital twins virtual replicas of physical assets enable real-time monitoring and simulation of offshore platforms, allowing operators to model various scenarios and make data-driven decisions regarding energy management (Chen *et al*., 2021). By leveraging these technologies, companies can enhance their ability to integrate renewable energy sources effectively and reduce overall energy consumption.

The decarbonization of the entire offshore supply chain is critical for achieving broader sustainability goals in the oil and gas industry. Integrating renewable energy into supply vessels and drilling operations can significantly reduce emissions associated with transportation and extraction activities (Fetisov *et al*., 2023). For example, supply vessels can be equipped with hybrid propulsion systems that utilize both conventional fuels and renewable energy sources, leading to lower operational costs and reduced environmental impact. Furthermore, logistics operations can be optimized through the use of renewable energy-powered technologies, such as electric vehicles for transporting materials and personnel to and from offshore installations. The long-term potential and future trends in renewable energy integration present substantial opportunities for the oil and gas industry. With the potential for full electrification of offshore platforms, advancements in floating renewable energy platforms and energy storage solutions, and the adoption of emerging technologies like AI and digital twins, the path toward sustainable offshore operations is becoming increasingly viable. Moreover, decarbonizing the entire offshore supply chain will further enhance the industry's efforts to reduce its carbon footprint (Khorasani *et al*., 2022). As these trends continue to evolve, the oil and gas sector can play a pivotal role in the global transition to a more sustainable energy future.

2.7. Case Studies of Renewable Energy Integration in Offshore Oil and Gas

The integration of renewable energy into offshore oil and gas operations represents a transformative approach to reducing greenhouse gas emissions and enhancing operational sustainability. This review examines two prominent case studies: the Hywind Tampen project in Norway and the Kincardine Offshore Wind Farm in the United Kingdom. Both projects exemplify the potential of renewable energy to power oil and gas platforms, addressing operational challenges while demonstrating scalability potential for future implementations.

Hywind Tampen, launched in 2020, is recognized as the world's first offshore wind farm specifically designed to power oil and gas platforms. Located in the North Sea, the project comprises 11 floating wind turbines, each with a capacity of 8.4 megawatts (MW), and aims to supply electricity to the Snorre and Gullfaks oil fields. The initiative marks a significant milestone in the industry by showcasing the viability of using offshore wind energy to support fossil fuel extraction operations. The operational challenges faced during the Hywind Tampen project were significant. One of the primary hurdles involved the installation and connection of the floating turbines to existing oil and gas infrastructure (Venegas, 2021). The floating design required specialized technology to secure the turbines in deep water, ensuring they remained stable and efficient in varying sea conditions. Additionally, integrating the wind farm with the energy demands of the oil platforms necessitated the development of sophisticated monitoring and control systems to manage power distribution effectively. Despite these challenges, the outcomes of the Hywind Tampen project have been promising. It is projected to reduce carbon dioxide emissions by approximately 200,000 tons per year, significantly contributing to Norway's climate goals. Furthermore, the successful operation of this wind farm has provided valuable insights into the operational dynamics of integrating renewable energy into oil and gas platforms, paving the way for future projects both in Norway and globally.

The Kincardine Offshore Wind Farm, located off the coast of Scotland, is another exemplary case of renewable energy integration in the oil and gas sector. As the largest floating wind farm in the world, Kincardine consists of six turbines with a total capacity of 50 MW. The project was developed to provide renewable energy to both local grids and offshore oil and gas platforms in the North Sea, illustrating the potential for hybrid energy solutions. Kincardine faced its own set of challenges, particularly regarding environmental conditions and logistics. The installation of floating wind turbines required extensive planning and coordination, given the harsh marine environment and variable weather conditions. Moreover, the project's success hinged on the development of efficient energy storage solutions to ensure a continuous power supply, especially during periods of low wind. This aspect highlighted the importance of robust infrastructure and technology in facilitating renewable energy integration into existing systems (Alotaibi *et al*., 2020). The lessons learned from Kincardine are invaluable for scaling up renewable energy integration in the offshore oil and gas sector. The project has demonstrated that floating wind farms can effectively coexist with oil and gas operations, providing a reliable and sustainable energy source. Additionally, Kincardine's experience has revealed the need for comprehensive regulatory frameworks and collaboration between government bodies, energy companies, and technology providers to overcome challenges and maximize the scalability of similar projects.

The case studies of Hywind Tampen and Kincardine Offshore Wind Farm illustrate the transformative potential of renewable energy integration in offshore oil and gas operations. Both projects have successfully addressed operational challenges, providing significant insights into the feasibility of using offshore wind energy to power oil platforms. As the industry continues to pursue sustainability goals, these case studies serve as valuable models for future renewable energy initiatives, underscoring the importance of innovation, collaboration, and effective planning in driving the transition toward greener energy solutions.

2.8. Challenges and Barriers to Widespread Adoption of Renewable Energy in Offshore Oil and Gas

The transition to renewable energy in offshore oil and gas operations offers a path toward greater sustainability and reduced emissions (Mohammad *et al*., 2021). However, several challenges and barriers must be addressed to facilitate the widespread adoption of these technologies. This review explores the technical and operational barriers, economic and financial constraints, and potential solutions to overcome these obstacles.

One of the most significant technical challenges in adopting renewable energy sources such as wind and solar is their inherent intermittency. Renewable energy generation fluctuates based on weather conditions, time of day, and seasonal variations. This variability can lead to inconsistent energy supply, complicating the energy management strategies necessary for offshore platforms that typically require a continuous and reliable energy source for operations such as drilling and processing. Integrating renewable energy systems with existing offshore infrastructure poses additional challenges. Many oil and gas installations were designed primarily for fossil fuel-based energy systems, which complicates the integration of renewable technologies (Dunlap, 2021). Upgrading infrastructure to accommodate wind turbines or solar panels may require extensive modifications and investment in new equipment. Additionally, energy storage solutions, such as batteries, are crucial for managing supply and demand; however, these technologies also come with their own set of technical and economic challenges.

The financial landscape for adopting renewable energy in offshore operations is fraught with challenges. High upfront costs associated with installing renewable energy technologies can deter investment. Offshore wind and solar projects often require substantial capital for development, equipment, and installation, which can exceed the initial budgets of many companies. Moreover, the uncertain returns on these investments, particularly in volatile energy markets, further complicate decision-making processes for stakeholders. Access to investment and financial incentives is another critical factor. Although there has been an increasing interest in green financing, the availability of capital specifically allocated for renewable energy projects in offshore oil and gas is still limited. Companies may face difficulty in securing the necessary funding to initiate these projects, particularly in regions where traditional fossil fuel investments remain the focus (Rempel and Gupta, 2022).

To address these barriers, comprehensive government policies are essential in incentivizing renewable energy use. Policymakers can implement tax credits, grants, and subsidies that make renewable energy projects more financially viable. Additionally, regulatory frameworks that streamline permitting processes and reduce bureaucratic hurdles can encourage investment in renewable technologies, creating a more attractive environment for stakeholders. Industry collaboration also plays a vital role in overcoming challenges (Jacobs, 2021). By fostering partnerships between oil and gas companies, technology providers, and research institutions, the sector can drive innovation in renewable energy integration. Collaborative efforts can lead to the development of more efficient technologies, improved energy management systems, and shared best practices that can enhance the overall feasibility of adopting renewable energy in offshore environments. Technological innovation remains a key solution to mitigating the challenges of renewable energy integration. Advances in energy storage, smart grid technology, and energy management systems can help optimize the use of renewable resources while ensuring reliability and efficiency (Tan *et al*., 2021). For instance, innovations such as floating wind turbines and deep-water solar installations can enhance energy generation capabilities in offshore settings, making it easier to incorporate renewables into existing operations.

While the widespread adoption of renewable energy in offshore oil and gas operations faces significant challenges, including technical barriers, economic constraints, and the need for collaboration, the potential benefits far outweigh these obstacles. By implementing supportive government policies, fostering industry partnerships, and encouraging technological innovations, stakeholders can pave the way for a more sustainable and efficient energy future in the offshore sector (Roesch *et al*., 2021). Addressing these challenges will not only contribute to reducing greenhouse gas emissions but also enhance the long-term viability of the oil and gas industry in an evolving energy landscape.

3. Conclusion

The integration of renewable energy into offshore oil and gas operations is crucial for decarbonizing the sector and addressing global climate challenges. By harnessing wind, solar, and marine energy, the oil and gas industry can significantly reduce its carbon footprint while continuing to meet energy demands. The feasibility of deploying these renewable technologies in offshore environments has been demonstrated through various projects, showcasing their potential to provide reliable and sustainable energy solutions.

As the oil and gas industry faces increasing pressure to transition to more environmentally friendly practices, the outlook for renewable energy integration is promising. Continued investment in renewable technologies, coupled with supportive policy frameworks, is essential to drive this transformation. Governments and industry stakeholders must collaborate to create incentives that facilitate the adoption of renewable energy solutions, ensuring that companies can overcome financial and technical barriers. Technological advancements will also play a critical role in the successful integration of renewable energy in offshore operations. Innovations in energy storage, smart grid technologies, and hybrid energy systems can enhance the efficiency and reliability of energy supply, making renewables a viable alternative to traditional fossil fuels. Ultimately, the successful integration of renewable energy in the oil and gas sector is not just a pathway to reducing emissions; it is a necessary step toward achieving long-term sustainability and meeting net-zero targets. By embracing renewable energy, the industry can secure its future while contributing to a more sustainable and resilient energy landscape.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Abbasi, K.R., Shahbaz, M., Zhang, J., Irfan, M. and Alvarado, R., 2022. Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy. *Renewable Energy*, *187*, pp.390-402.

[2] Abdulrahman, I., Máša, V. and Teng, S.Y., 2021. Process intensification in the oil and gas industry: A technological framework. *Chemical Engineering and Processing-Process Intensification*, *159*, p.108208.

[3] Abualigah, L., Zitar, R.A., Almotairi, K.H., Hussein, A.M., Abd Elaziz, M., Nikoo, M.R. and Gandomi, A.H., 2022. Wind, solar, and photovoltaic renewable energy systems with and without energy storage optimization: A survey of advanced machine learning and deep learning techniques. *Energies*, *15*(2), p.578.

[4] Agupugo, C.P. and Tochukwu, M.F.C., A Model To Assess The Economic Viability Of Renewable Energy Microgrids: A Case Study Of Imufu Nigeria.

[5] Alotaibi, I., Abido, M.A., Khalid, M. and Savkin, A.V., 2020. A comprehensive review of recent advances in smart grids: A sustainable future with renewable energy resources. *Energies*, *13*(23), p.6269.

[6] Al-Sarihi, A. and Mansouri, N., 2022. Renewable energy development in the Gulf cooperation council countries: Status, barriers, and policy options. *Energies*, *15*(5), p.1923.

[7] Al-Shetwi, A.Q., 2022. Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges. *Science of The Total Environment*, *822*, p.153645.

[8] Amir, M., Zaheeruddin and Haque, A., 2022. Intelligent based hybrid renewable energy resources forecasting and real time power demand management system for resilient energy systems. *Science Progress*, *105*(4), p.00368504221132144.

[9] Arent, D.J., Green, P., Abdullah, Z., Barnes, T., Bauer, S., Bernstein, A., Berry, D., Berry, J., Burrell, T., Carpenter, B. and Cochran, J., 2022. Challenges and opportunities in decarbonizing the US energy system. *Renewable and Sustainable Energy Reviews*, *169*, p.112939.

[10] Barooni, M., Ashuri, T., Velioglu Sogut, D., Wood, S. and Ghaderpour Taleghani, S., 2022. Floating offshore wind turbines: Current status and future prospects. *Energies*, *16*(1), p.2.

[11] Blazquez, J., Dale, S., Jefferiss, P., Heffron, R.J., Herbertson, J., West, R. and Hegland, J., 2020. Decarbonization pathways for oil and gas. In *Oxford Energy Forum* (Vol. 121, pp. 1-40).

[12] Braga, J., Santos, T., Shadman, M., Silva, C., Assis Tavares, L.F. and Estefen, S., 2022. Converting offshore oil and gas infrastructures into renewable energy generation plants: an economic and technical analysis of the decommissioning delay in the Brazilian Case. *Sustainability*, *14*(21), p.13783.

[13] Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A.S., Aghahosseini, A., Gulagi, A., Solomon, A.A., Keiner, D., Lopez, G. and Østergaard, P.A., 2022. On the history and future of 100% renewable energy systems research. *IEEE Access*, *10*, pp.78176-78218.

[14] Chen, B.Q., Soares, C.G. and Videiro, P.M., 2021. Review of digital twin of ships and offshore structures. In *Maritime Technology and Engineering 5 Volume 1* (pp. 445-451). CRC Press.

[15] Chen, X., Wang, M., Wang, B., Hao, H., Shi, H., Wu, Z., Chen, J., Gai, L., Tao, H., Zhu, B. and Wang, B., 2023. Energy consumption reduction and sustainable development for oil & gas transport and storage engineering. *Energies*, *16*(4), p.1775.

[16] Cherepovitsyn, A., Kazanin, A. and Rutenko, E., 2023. Strategic Priorities for Green Diversification of Oil and Gas Companies. *Energies*, *16*(13), p.4985.

[17] Coles, D., Angeloudis, A., Goss, Z. and Miles, J., 2021. Tidal stream vs. wind energy: The value of cyclic power when combined with short-term storage in hybrid systems. *Energies*, *14*(4), p.1106.

[18] Considine, J.I., Cooke, D., Wood, G., Cote, S. and Aldayel, A., 2023. The stability of world oil markets and the potential for oil shocks1. In *A Research Agenda for Energy Politics* (pp. 3-19). Edward Elgar Publishing.

[19] Datta, U., Kalam, A. and Shi, J., 2021. A review of key functionalities of battery energy storage system in renewable energy integrated power systems. *Energy Storage*, *3*(5), p.e224.

[20] Dunlap, A., 2021. Does renewable energy exist? Fossil fuel+ technologies and the search for renewable energy. *A critical approach to the social acceptance of renewable energy infrastructures: Going beyond green growth and sustainability*, pp.83-102.

[21] Fetisov, V., Gonopolsky, A.M., Davardoost, H., Ghanbari, A.R. and Mohammadi, A.H., 2023. Regulation and impact of VOC and CO2 emissions on low-carbon energy systems resilient to climate change: A case study on an environmental issue in the oil and gas industry. *Energy Science & Engineering*, *11*(4), pp.1516-1535.

[22] Friedmann, J., Zapantis, A., Page, B., Consoli, C., Fan, Z., Havercroft, I., Liu, H., Ochu, E., Raji, N., Rassool, D. and Sheerazi, H., 2020. Net-zero and geospheric return: actions today for 2030 and beyond. *Center on Global Energy Policy*.

[23] Ghorbani, Y., Zhang, S.E., Nwaila, G.T., Bourdeau, J.E. and Rose, D.H., 2023. Embracing a diverse approach to a globally inclusive green energy transition: Moving beyond decarbonisation and recognising realistic carbon reduction strategies. *Journal of Cleaner Production*, p.140414.

[24] Gispert, I., Hindley, J.W., Pilkington, C.P., Shree, H., Barter, L.M., Ces, O. and Elani, Y., 2022. Stimuli-responsive vesicles as distributed artificial organelles for bacterial activation. *Proceedings of the National Academy of Sciences*, *119*(42), p.e2206563119.

[25] Habert, G., Miller, S.A., John, V.M., Provis, J.L., Favier, A., Horvath, A. and Scrivener, K.L., 2020. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, *1*(11), pp.559-573.

[26] Hartmann, J., Inkpen, A.C. and Ramaswamy, K., 2021. Different shades of green: Global oil and gas companies and renewable energy. *Journal of International Business Studies*, *52*, pp.879-903.

[27] Hassan, Q., Algburi, S., Sameen, A.Z., Salman, H.M. and Jaszczur, M., 2023. A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*, p.101621.

[28] Hastings, A. and Smith, P., 2020. Achieving net zero emissions requires the knowledge and skills of the oil and gas industry. *Frontiers in Climate*, *2*, p.601778.

[29] Huang, G., Tang, Y., Chen, X., Chen, M. and Jiang, Y., 2023. A comprehensive review of floating solar plants and potentials for offshore applications. *Journal of Marine Science and Engineering*, *11*(11), p.2064.

[30] Hunt, J.D., Nascimento, A., Nascimento, N., Vieira, L.W. and Romero, O.J., 2022. Possible pathways for oil and gas companies in a sustainable future: From the perspective of a hydrogen economy. *Renewable and Sustainable Energy Reviews*, *160*, p.112291.

[31] Igogo, T., Awuah-Offei, K., Newman, A., Lowder, T. and Engel-Cox, J., 2021. Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches. *Applied Energy*, *300*, p.117375.

[32] Jacobs, S.B., 2021. Agency genesis and the energy transition. *Columbia Law Review*, *121*(3), pp.835-936.

[33] Jegede, A.O. and Adejonwo, O. eds., 2023. *Climate change justice and human rights: an African perspective*. Pretoria University Law Press.

[34] Ji, M. and Wang, J., 2021. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. *International Journal of Hydrogen Energy*, *46*(78), pp.38612-38635.

[35] Jiang, Z., 2021. Installation of offshore wind turbines: A technical review. *Renewable and Sustainable Energy Reviews*, *139*, p.110576.

[36] Kazimierczuk, K., Henderson, C., Duffy, K., Hanif, S., Bhattacharya, S., Biswas, S., Jacroux, E., Preziuso, D., Wu, D., Bhatnagar, D. and Tarekegne, B., 2023. A socio-technical assessment of marine renewable energy potential in coastal communities. *Energy Research & Social Science*, *100*, p.103098.

[37] Khorasani, M., Sarker, S., Kabir, G. and Ali, S.M., 2022. Evaluating strategies to decarbonize oil and gas supply chain: Implications for energy policies in emerging economies. *Energy*, *258*, p.124805.

[38] McLaurin, D., Paulin, M., Peng, C. and Yadlapati, R., 2021, August. The Use of Offshore Wind to Reduce Greenhouse Gas Emissions in Offshore Hydrocarbon Production-A Case Study. In *Offshore Technology Conference* (p. D031S035R007). OTC.

[39] Mohammad, N., Mohamad Ishak, W.W., Mustapa, S.I. and Ayodele, B.V., 2021. Natural gas as a key alternative energy source in sustainable renewable energy transition: a mini review. *Frontiers in Energy Research*, *9*, p.625023.

[40] Muhtadi, A., Pandit, D., Nguyen, N. and Mitra, J., 2021. Distributed energy resources based microgrid: Review of architecture, control, and reliability. *IEEE Transactions on Industry Applications*, *57*(3), pp.2223-2235.

[41] Neill, S.P., Haas, K.A., Thiébot, J. and Yang, Z., 2021. A review of tidal energy—Resource, feedbacks, and environmental interactions. *Journal of Renewable and Sustainable Energy*, *13*(6).

[42] Ogolo, N.A., Anih, O.C. and Onyekonwu, M.O., 2022. Sources and effects of environmental pollution from oil and gas industrial operations. *Arabian Journal of Chemical and Environmental Research*, *9*(01), pp.98-121.

[43] Oyekale, J., Petrollese, M., Tola, V. and Cau, G., 2020. Impacts of renewable energy resources on effectiveness of grid-integrated systems: Succinct review of current challenges and potential solution strategies. *Energies*, *13*(18), p.4856.

[44] Papadis, E. and Tsatsaronis, G., 2020. Challenges in the decarbonization of the energy sector. *Energy*, *205*, p.118025.

[45] Praveen, R.P., Keloth, V., Abo-Khalil, A.G., Alghamdi, A.S., Eltamaly, A.M. and Tlili, I., 2020. An insight to the energy policy of GCC countries to meet renewable energy targets of 2030. *Energy Policy*, *147*, p.111864.

[46] Qadir, S.A., Al-Motairi, H., Tahir, F. and Al-Fagih, L., 2021. Incentives and strategies for financing the renewable energy transition: A review. *Energy Reports*, *7*, pp.3590-3606.

[47] Rempel, A. and Gupta, J., 2022. Equitable, effective, and feasible approaches for a prospective fossil fuel transition. *Wiley Interdisciplinary Reviews: Climate Change*, *13*(2), p.e756.

[48] Riboldi, L., Alves, E.F., Pilarczyk, M., Tedeschi, E. and Nord, L.O., 2020. Optimal design of a hybrid energy system for the supply of clean and stable energy to offshore installations. *Frontiers in Energy Research*, *8*, p.607284.

[49] Roesch, R., Boshell, F., Ocenic, E., Salgado, A., Hecke, J., Castellanos, G., Gielen, D., Abunofal, M., Ratka, S. and Abdel-Latif, A., 2020. Fostering a blue economy: Offshore renewable energy.

[50] Satymov, R., Bogdanov, D. and Breyer, C., 2021. The value of fast transitioning to a fully sustainable energy system: The case of Turkmenistan. *IEEE Access*, *9*, pp.13590-13611.

[51] Shotorbani, A.M., Zeinal-Kheiri, S., Chhipi-Shrestha, G., Mohammadi-Ivatloo, B., Sadiq, R. and Hewage, K., 2021. Enhanced real-time scheduling algorithm for energy management in a renewable-integrated microgrid. *Applied Energy*, *304*, p.117658.

[52] Soukissian, T., O'Hagan, A.M., Azzellino, A., Boero, F., Brito e Melo, A., Comiskey, P., Gao, Z., Howell, D., Le Boulluec, M., Maisondieu, C. and Scott, B.E., 2023. European offshore renewable energy: towards a sustainable future.

[53] Tan, Y., Li, H.X., Cheng, J.C., Wang, J., Jiang, B., Song, Y. and Wang, X., 2021. Cost and environmental impact estimation methodology and potential impact factors in offshore oil and gas platform decommissioning: A review. *Environmental Impact Assessment Review*, *87*, p.106536.

[54] Temizel, C., Aydin, H., Hosgor, F.B., Yegin, C. and Kabir, C.S., 2023. Green Energy Sources Reduce Carbon Footprint of Oil & Gas Industry Processes: A Review. *Journal of Energy and Power Technology*, *5*(1), pp.1-25.

[55] Tzankova, Z., 2020. Public policy spillovers from private energy governance: New opportunities for the political acceleration of renewable energy transitions. *Energy Research & Social Science*, *67*, p.101504.

[56] Venegas, T.C.P., 2021. Floating Turbines: The Next Generation of Offshore Wind Farms. *Tex. J. Oil Gas & Energy L.*, *16*, p.71.

[57] Vidal, P.D.C.J., González, M.O.A., de Melo, D.C., de Oliveira Ferreira, P., Sampaio, P.G.V. and Lima, L.O., 2022. Conceptual framework for the decommissioning process of offshore oil and gas platforms. *Marine Structures*, *85*, p.103262.

[58] Yuan, Y., Wang, J., Yan, X., Shen, B. and Long, T., 2020. A review of multi-energy hybrid power system for ships. *Renewable and Sustainable Energy Reviews*, *132*, p.110081.

[59] Zhang, Q., Zhang, H., Yan, Y., Yan, J., He, J., Li, Z., Shang, W. and Liang, Y., 2021. Sustainable and clean oilfield development: How access to wind power can make offshore platforms more sustainable with production stability. *Journal of Cleaner Production*, *294*, p.126225.

[60] Zhou, Q., Wang, S., Liu, J., Hu, X., Liu, Y., He, Y., He, X. and Wu, X., 2022. Geological evolution of offshore pollution and its long-term potential impacts on marine ecosystems. *Geoscience Frontiers*, *13*(5), p.101427.

[61] Zhou, Q., Wu, J., Imran, M., Nassani, A.A., Binsaeed, R.H. and Zaman, K., 2023. Examining the trade-offs in clean energy provision: Focusing on the relationship between technology transfer, renewable energy, industrial growth, and carbon footprint reduction. *Heliyon*, *9*(10).

[62] Zichittella, G. and Pérez-Ramírez, J., 2021. Status and prospects of the decentralised valorisation of natural gas into energy and energy carriers. *Chemical Society Reviews*, *50*(5), pp.2984-3012.

[63] Zou, X., Qiu, R., Yuan, M., Liao, Q., Yan, Y., Liang, Y. and Zhang, H., 2021. Sustainable offshore oil and gas fields development: Techno-economic feasibility analysis of wind–hydrogen–natural gas nexus. *Energy Reports*, *7*, pp.4470-4482.