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# A conceptual model for cost-effective seismic acquisition in complex offshore environments through data optimization and technological innovation

Elemele Ogu [1,*], Peter Ifechukwude Egbumokei [2], Ikiomoworio Nicholas Dienagha [3] and Wags Numoipiri Digitemie [4]

[1] *TotalEnergies Exploration and Production Nigeria Limited, Nigeria.*
[2] *Shell Nigeria Gas (SEN/ SNG), Nigeria.*
[3] *Shell Petroleum Development Company, Lagos, Nigeria.*
[4] *Shell Energy Nigeria PLC.*

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## Abstract

Seismic acquisition in complex offshore environments poses significant challenges, including high costs, intricate subsurface structures, and operational risks. This paper presents a conceptual model for achieving cost-effective seismic acquisition by leveraging data optimization techniques and cutting-edge technological innovations. The model integrates advanced geophysical methods, machine learning algorithms, and real-time data analytics to optimize survey design, streamline data acquisition processes, and enhance imaging accuracy. Key components of the proposed model include adaptive sampling strategies, automated quality control systems, and hybrid acquisition technologies that combine ocean-bottom nodes (OBN) with towed streamers. By employing machine learning models trained on historical seismic data, the approach predicts optimal survey parameters and identifies potential data gaps, minimizing redundant data collection and operational costs. Additionally, the integration of real-time data processing ensures swift adjustments to acquisition strategies, reducing downtime and improving data quality in challenging conditions. This model emphasizes the use of eco-friendly technologies, such as autonomous seismic nodes powered by renewable energy, to align with sustainability goals while maintaining operational efficiency. The proposed framework also incorporates risk management protocols to mitigate environmental and technical risks, ensuring compliance with regulatory standards and industry best practices. A case study simulation demonstrates the model's effectiveness in reducing acquisition costs by up to 30% while achieving high-resolution subsurface imaging in a geologically complex offshore basin. The findings underscore the potential of data optimization and technological innovation to revolutionize seismic acquisition in offshore environments, enabling resource-efficient and sustainable exploration practices. This conceptual model provides a pathway for industry stakeholders to balance cost-efficiency, technological advancement, and environmental stewardship in seismic exploration. Future research directions include the integration of artificial intelligence for real-time decision-making and the development of advanced visualization tools for subsurface interpretation.

**Keywords:** Seismic Acquisition; Offshore Environments; Data Optimization; Machine Learning; Cost Efficiency; Ocean-Bottom Nodes; Hybrid Technologies; Real-Time Analytics; Sustainable Exploration; Risk Management

## 1. Introduction

Seismic acquisition in offshore environments is a crucial element in the exploration and development of hydrocarbon resources. However, it comes with significant challenges that must be addressed to ensure operational efficiency and environmental sustainability. One of the primary challenges is the high cost associated with offshore seismic operations

* Corresponding author: Elemele Ogu

(Elujide, et al., 2021). These costs are driven by the need for specialized equipment, advanced technologies, and the complexities of working in harsh offshore environments. The intricate and often difficult-to-navigate subsurface structures further complicate the process, making accurate data collection and interpretation both technically demanding and expensive (Oladosu, et al., 2021). Additionally, operators must contend with strict environmental regulations aimed at minimizing the ecological impact of seismic activities. These pressures require solutions that not only optimize operational costs but also adhere to environmental and regulatory standards.

To address these challenges, there is an increasing need for technological innovation that promotes cost-efficiency without compromising the quality of data collected. Technological advancements, such as improved seismic sensors, more efficient data processing algorithms, and the integration of machine learning and artificial intelligence, have the potential to significantly reduce operational costs while enhancing the quality and precision of seismic data. By optimizing the data acquisition process, these innovations enable a more effective and cost-efficient approach to seismic surveys in offshore environments (Bidemi, et al., 2021, Elujide, et al., 2021). Moreover, the integration of these technologies ensures that seismic acquisition can meet the growing demand for sustainable and environmentally responsible exploration practices. Therefore, adopting a conceptual model that incorporates both data optimization techniques and cutting-edge technological innovations is essential to reducing costs and environmental impacts while maximizing the value of seismic data.

## 2. Literature Review

Seismic acquisition plays a critical role in offshore exploration, providing essential data on subsurface geological formations that enable the identification and development of hydrocarbon reserves. However, seismic operations in offshore environments are often costly and complex due to the specialized equipment required, the challenges of accessing remote locations, and the intricacies of the subsurface structures. In recent years, traditional seismic acquisition methods have come under scrutiny for their inefficiency, high costs, and environmental impact (Abdul Rahim, et al., 2020, Han, Cader & Brownless, 2021). As such, the exploration industry is increasingly turning toward new technologies and data optimization strategies to improve cost-effectiveness and environmental sustainability.

Traditional seismic survey techniques, such as towed streamers and ocean-bottom nodes (OBN), have been the mainstay of offshore seismic acquisition for decades. Towed streamers involve deploying a series of hydrophone arrays behind a survey vessel to record seismic waves reflected from subsurface structures. These systems are relatively straightforward and widely used in offshore exploration, but they come with significant limitations (Harris, 2018, Silva & Al Kaabi, 2017, Pan, et al., 2019). One of the major drawbacks is the high cost associated with deploying and maintaining the equipment. The vessels required for towing the streamers are expensive to operate, and the large-scale deployment of cables and other hardware can result in prolonged survey times, which increases costs. Additionally, towed streamer surveys often struggle to obtain high-resolution data at greater depths or in areas with complex subsurface structures, such as fault zones or deepwater reservoirs. This limitation in data quality is due to the inability of towed streamers to provide a dense enough coverage of the seabed, particularly in challenging environments.

Ocean-bottom nodes, on the other hand, offer a more effective solution in some offshore settings, particularly in deepwater environments. These autonomous devices are placed on the ocean floor and record seismic data from waves that travel through the subsurface and reflect back to the nodes. OBN systems are able to capture more detailed and accurate data, especially in areas with complicated geological formations. However, their use is also limited by significant operational challenges (Ampilov, Vladov & Tokarev, 2019). Deploying and retrieving OBN systems is a time-consuming and expensive process. The need for specialized equipment, as well as the requirement to deploy hundreds or thousands of nodes across a survey area, contributes to the overall cost of the operation. Moreover, ocean-bottom nodes are difficult to maintain and service, especially in remote locations, which further increases operational risks and costs. Sircar, et al., 2021, presented exploration outline for data processing and interpretation using machine learning technique as shown in figure 1.

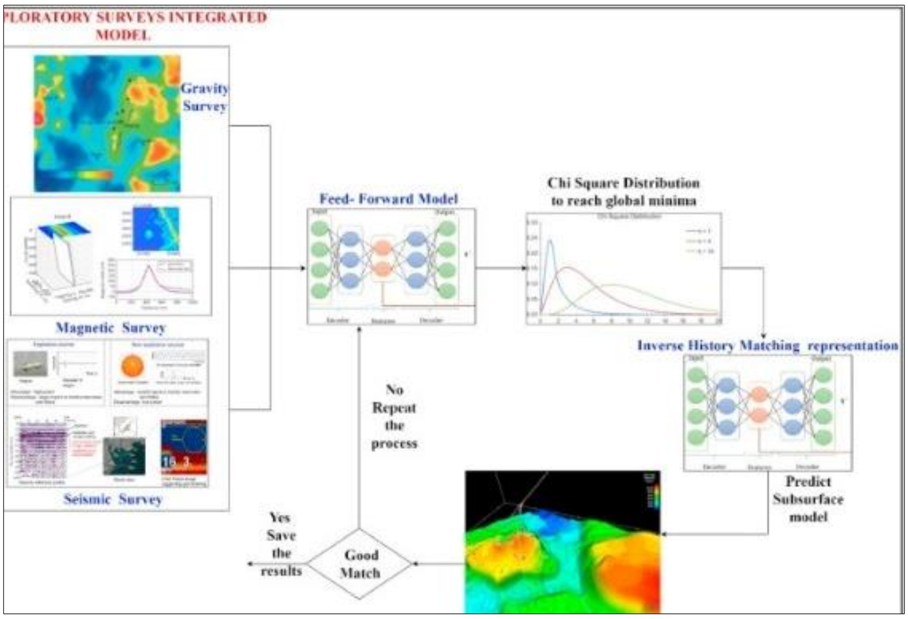


**Figure 1** Exploration outline for data processing and interpretation using machine learning technique (Sircar, et al., 2021)

Despite these limitations, there has been considerable progress in seismic acquisition technologies, driven by advancements in hybrid systems, machine learning, and autonomous devices. The integration of machine learning into seismic survey design represents one of the most promising developments in recent years (Ampomah, et al., 2017, Holdaway & Irving, 2017, Sambo, et al., 2020). Machine learning algorithms can process vast amounts of historical seismic data to identify patterns and trends, thereby enabling more predictive and adaptive survey designs. Instead of relying on conventional survey methods that follow predetermined lines or patterns, machine learning models can predict where seismic activity is likely to be the most productive, reducing survey time and increasing the efficiency of data collection. These predictive survey designs help operators prioritize survey areas with the highest potential for new discoveries while minimizing redundant data collection in less promising areas.

In addition to machine learning, hybrid acquisition systems are becoming increasingly prevalent in offshore seismic operations. Hybrid systems combine the strengths of both towed streamers and ocean-bottom nodes, offering a more versatile and cost-effective solution for seismic data acquisition. For instance, some hybrid systems use towed streamers for broader coverage in less complex regions of a survey area while deploying ocean-bottom nodes in areas of particular interest, such as deepwater reservoirs or geological features with more intricate structures (Andrews, Playfoot & Augustus, 2015, Laws, et al., 2019). This combination allows for the collection of high-resolution data where needed, without the high costs and operational delays associated with using ocean-bottom nodes throughout an entire survey area. Hybrid systems also offer more flexibility, allowing operators to adjust their survey methods based on real-time data, which further contributes to the overall cost-efficiency of the operation.

Autonomous seismic nodes are another key innovation that has significantly impacted the cost-effectiveness of seismic acquisition in offshore environments. These nodes operate without the need for a continuous connection to surface vessels or survey equipment, making them a more efficient and cost-effective solution for data collection. Autonomous nodes are deployed on the seabed, where they record seismic data and transmit it back to surface stations when needed. This technology eliminates the need for cables, which reduces the complexity of operations and the associated costs (Audu, et al., 2016, , Hendry, et al., 2021, Ikoro, 2020). Moreover, autonomous nodes can be deployed in areas that are difficult or dangerous to access with traditional equipment, such as deepwater zones or areas with challenging weather conditions. As such, these nodes represent a promising technology for minimizing operational costs while still providing accurate and detailed seismic data. The seismic data acquisition chain by Liu, 2015 is shown in figure 2.

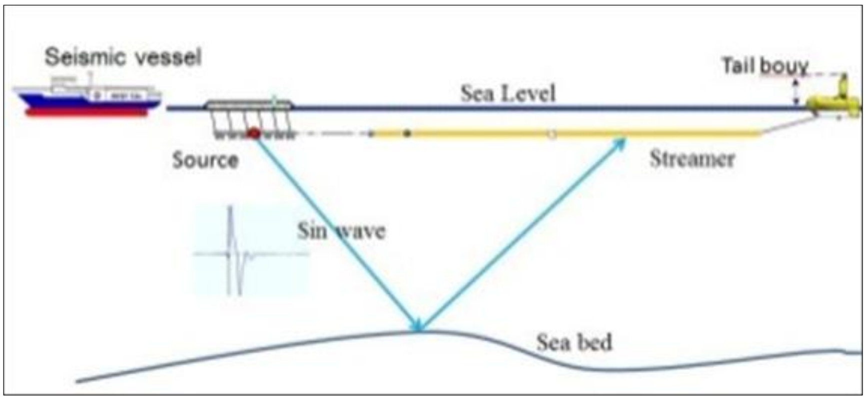


**Figure 2** The seismic data acquisition chain (Liu, 2015)

Another technological advancement that has the potential to revolutionize offshore seismic operations is the use of renewable energy solutions. Traditionally, seismic surveys have relied heavily on fossil fuels to power the equipment, especially in remote offshore areas where access to the electrical grid is limited. However, renewable energy sources, such as solar and wind power, are increasingly being integrated into seismic operations to reduce the carbon footprint and lower energy costs (Birin & Maglić, 2020, Jack, 2017, Levin, et al., 2019). By using renewable energy to power seismic equipment, operators can reduce their reliance on costly and polluting diesel generators, resulting in a more sustainable and cost-effective operation. Additionally, the use of renewable energy sources helps operators meet growing environmental regulations and industry demands for greener practices, making it a win-win solution for both the environment and the bottom line.

Data optimization plays a critical role in improving the cost-effectiveness of seismic acquisition, particularly in complex offshore environments. One of the primary strategies for optimizing seismic data acquisition is minimizing redundant data collection. Seismic surveys typically involve collecting large amounts of data, but much of it can be repetitive and unnecessary (Bohi, 2014, Jenkins, Chadwick & Hovorka, 2015, Sun, et al., 2021). By using advanced data processing techniques, such as real-time data analytics, operators can identify areas where further data collection is unnecessary and focus resources on areas that are more likely to yield valuable results. This targeted approach helps reduce operational time and costs while still providing the necessary data for accurate subsurface imaging.

Real-time data analytics is another key strategy for optimizing seismic acquisition. With the ability to analyze data as it is being collected, operators can make immediate adjustments to the survey parameters, such as changing the survey area or adjusting the seismic sources. This adaptive approach allows for a more efficient use of resources, as it ensures that operators can respond to changing conditions and optimize data collection in real-time (Büyüközkan & Göçer, 2018, Ketineni, et al., 2020, Thomas, et al., 2020). The ability to monitor data quality during the survey also reduces the likelihood of collecting poor-quality data that would later require reprocessing, further saving time and money. Moreover, adaptive survey strategies enable operators to reduce the environmental impact of seismic operations by minimizing the amount of time spent in sensitive areas, such as marine protected zones or critical habitats.

In conclusion, the seismic acquisition methods currently used in offshore environments face several challenges, including high costs, long operational timelines, and limited data quality. However, technological innovations such as machine learning, hybrid acquisition systems, autonomous seismic nodes, and renewable energy solutions are helping to address these challenges by improving efficiency and reducing costs (Chi, Wang & Jiao, 2015, Khan, Gupta & Gupta, 2020, Wilson, Nunn & Luheshi, 2021). Moreover, data optimization strategies such as minimizing redundant data collection and employing real-time data analytics allow for a more targeted and adaptive approach to seismic surveying, further enhancing the cost-effectiveness of offshore seismic operations. By leveraging these advancements, the offshore exploration industry can achieve greater efficiency, reduce environmental impact, and maximize resource recovery in complex offshore environments.

### 2.1. Conceptual Model Framework

The increasing demand for cost-effective seismic acquisition in offshore environments has prompted a reevaluation of traditional methods and the adoption of new technologies that leverage data optimization and innovative approaches. A conceptual model framework for seismic acquisition focuses on improving efficiency, reducing costs, and minimizing environmental impact through the integration of advanced technologies and strategies (Dekker & Thakkar, 2018, Mondol, 2015, Salehi & Burgueño, 2018). By adopting data-driven survey designs, utilizing hybrid acquisition technologies, integrating real-time data analytics, and emphasizing sustainability, the framework aims to optimize seismic operations in complex offshore environments.

At the core of this conceptual model is the use of data-driven survey design, which focuses on optimizing data collection while minimizing unnecessary redundancy. Adaptive sampling techniques, which adjust the survey parameters in real-time based on the data collected, enable more efficient seismic acquisition. By dynamically determining where and how to collect seismic data, adaptive sampling techniques help ensure that only the most relevant and useful data is gathered, which reduces operational time and costs (Desai, Pandian & Vij, 2021, Oguntoye & Oguntoye, 2021). In practice, this can mean changing the frequency or location of seismic sources based on the feedback provided by initial measurements, allowing for a more targeted survey approach. Predictive models that utilize historical seismic data play an essential role in this adaptive design. These models analyze past survey results to forecast areas of interest, thereby helping operators prioritize regions with the highest potential for resource discovery. By integrating predictive models into the survey design, seismic operations can be tailored to specific geological formations, ensuring that resources are allocated efficiently and that survey time is minimized. Sircar, et al., 2021, presented reservoir modelling outline using artificial neural network as shown in figure 3.

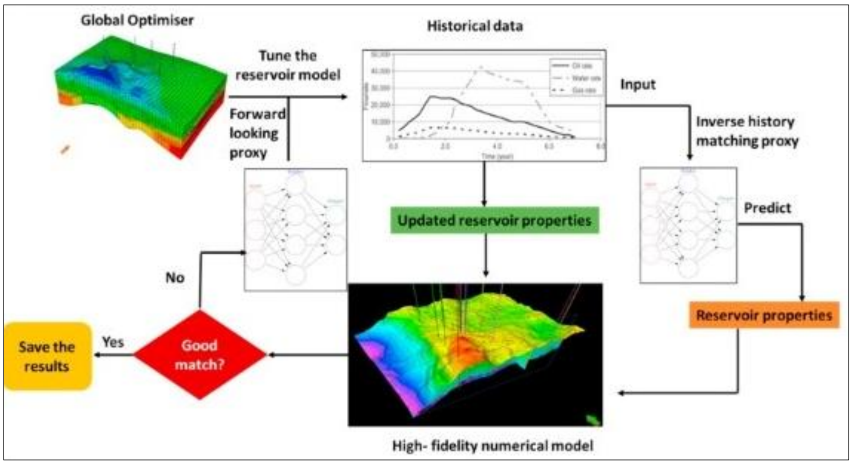


**Figure 3** Reservoir modelling outline using artificial neural network (Sircar, et al., 2021)

Hybrid acquisition technologies, another critical component of the conceptual model, offer a way to combine the strengths of different seismic acquisition methods to improve coverage and data quality. By combining ocean-bottom nodes (OBN) with towed streamers, operators can leverage the broad coverage and cost-effectiveness of towed streamers for large areas while obtaining the high-resolution data that ocean-bottom nodes can provide in more complex regions (Xinmin, et al., 2021, Yuan & Wood, 2018, Zou, et al., 2020). Ocean-bottom nodes are particularly effective in deepwater and challenging geological environments where towed streamers struggle to provide accurate data. These nodes are deployed on the seafloor and record seismic waves reflected from subsurface structures, offering greater accuracy in regions with complex geological features. The integration of these two methods creates a hybrid system that provides comprehensive coverage and high-quality data, making it particularly suitable for offshore environments where subsurface structures can be difficult to map.

Despite the benefits, hybrid systems come with challenges. For one, they require careful coordination between the two acquisition methods, which can increase operational complexity. The deployment and retrieval of ocean-bottom nodes, in particular, can be time-consuming and costly, especially in remote or deepwater locations. The technology also requires significant expertise in data integration, as the data from both methods must be synchronized and processed together to form a cohesive and accurate picture of the subsurface (Xu, et al., 2018, Yang, et al., 2021, Zhang, et al., 2021). However, the advantages of hybrid systems, including the ability to tailor acquisition methods to the specific geological conditions, outweigh these challenges and contribute significantly to the overall cost-effectiveness of seismic operations.

Real-time data analytics and processing are central to the conceptual model, enabling immediate feedback and adaptive survey strategies. Automated quality control and data validation technologies can rapidly assess the integrity of the seismic data being collected, allowing operators to quickly identify any issues with data quality. This automated process eliminates the need for manual checks and reduces the risk of human error, leading to faster, more accurate data validation (Dhar, et al., 2020, Levin, et al., 2019, Suthersan, et al., 2016). Furthermore, real-time data analytics allows operators to make adjustments to the acquisition parameters immediately based on the quality of the data being collected. For example, if the data from one area of the survey is deemed insufficient or of low quality, operators can change the survey approach on the fly, such as adjusting the seismic source or changing the deployment configuration. This adaptive feedback loop enhances the overall efficiency of seismic acquisition, reducing operational costs and preventing wasted resources on ineffective data collection.

Another important aspect of real-time data processing is the ability to minimize the amount of data collected without compromising the quality of the results. Through the use of advanced algorithms and machine learning models, real-time processing can identify areas where additional data is redundant or unnecessary. This targeted approach ensures that resources are focused on collecting the most valuable data, further reducing the cost of seismic surveys (Dindoruk, Ratnakar & He, 2020, Poppitt, et al., 2018, Trevathan, 2020). Furthermore, real-time adjustments to the acquisition parameters allow for a more sustainable approach to seismic operations by limiting the impact of the survey on the surrounding environment. For instance, if the survey is taking place near sensitive marine ecosystems, real-time feedback can help reduce the duration and intensity of seismic activity in those areas, minimizing the potential for disturbance to marine life.

Sustainability is an increasingly important consideration in offshore seismic acquisition, and the conceptual model framework incorporates eco-friendly innovations to address environmental concerns. One such innovation is the use of autonomous nodes powered by renewable energy sources. Traditional seismic acquisition methods often rely on diesel generators or other fossil fuel-based power sources, which contribute to both operational costs and environmental pollution (Djuraev, Jufar & Vasant, 2017, Nobre & Tavares, 2017). Autonomous nodes, however, can be powered by renewable energy, such as solar or wind power, which reduces the carbon footprint of seismic operations. These autonomous nodes are capable of operating independently, without the need for a continuous connection to surface vessels, which further reduces the environmental impact of the operations. By leveraging renewable energy, operators can ensure that seismic surveys are conducted in a more sustainable manner while also reducing energy costs and dependence on fossil fuels.

Moreover, minimizing environmental impact is an overarching goal in this conceptual model, and innovations in seismic technology play a crucial role in achieving this objective. The use of hybrid acquisition systems and real-time data analytics allows for a more efficient use of resources, which means that surveys can be completed in a shorter timeframe with less environmental disruption (Dubos-Sallée, et al., 2020, Nguyen, Gosine & Warrian, 2020). By focusing data collection efforts on the most relevant areas, operators can minimize the physical footprint of seismic surveys and reduce the time spent in sensitive marine areas. Additionally, advancements in data optimization techniques, such as adaptive sampling, help ensure that the seismic acquisition process is as precise and efficient as possible, further reducing the overall environmental impact.

In conclusion, the conceptual model for cost-effective seismic acquisition in complex offshore environments emphasizes the integration of data optimization, technological innovation, and sustainability to improve the efficiency and reduce the costs of seismic operations. By adopting data-driven survey designs, utilizing hybrid acquisition technologies, incorporating real-time data analytics, and focusing on eco-friendly innovations, the model aims to enhance the overall effectiveness of seismic surveys while minimizing their environmental footprint (Echarte, Rodríguez & López, 2019, Salako, 2015, Williams, et al., 2019). The adoption of these innovative approaches will help the offshore exploration industry meet the increasing demand for cost-effective, high-quality seismic data while adhering to sustainability goals and environmental regulations. This conceptual framework provides a comprehensive approach to seismic acquisition, addressing the challenges of complex offshore environments and laying the groundwork for more efficient, responsible, and cost-effective seismic operations in the future.

## 3. Methodology

The methodology for developing a conceptual model for cost-effective seismic acquisition in complex offshore environments through data optimization and technological innovation revolves around a structured approach to designing, implementing, and evaluating seismic acquisition strategies. This process is rooted in the integration of advanced technologies and data-driven techniques aimed at optimizing survey design, improving efficiency, and minimizing environmental impact. The methodology comprises several key stages, including data collection and preliminary analysis, survey design optimization, integration of hybrid technologies, real-time data processing and quality control, and cost and efficiency evaluation (Elijah, et al., 2021, Mateeva, et al., 2016, Wang, et al., 2017).

The first step involves data collection and preliminary analysis, which begins with selecting a complex offshore environment to serve as the case study. This environment could be characterized by challenging subsurface structures, such as deepwater fields with complex geology, or operational difficulties, like adverse weather conditions or remote locations. The selection process considers factors such as the region's geological characteristics, the availability of historical seismic data, and its relevance to the industry's exploration and resource recovery needs (Elijah, et al., 2021, Nanda, 2021, Sircar, et al., 2021). Once the offshore environment is chosen, historical seismic data is gathered along with environmental factors, such as current sea conditions, weather patterns, and marine life considerations. This data provides a foundation for understanding the area's seismic activity and identifying any challenges related to data collection in the environment. Analyzing this information helps in selecting appropriate survey parameters and forms the basis for future predictive modeling.

Survey design optimization is the next stage, where advanced methods such as machine learning models are employed to predict the most efficient survey parameters based on the gathered data. By utilizing machine learning algorithms, predictive models can identify areas where seismic activity is most likely to yield useful data, thus reducing the need for extensive survey coverage. These models can also optimize the placement of sensors and determine the ideal frequency of seismic sources, considering factors such as depth, target reservoir types, and environmental constraints (Emami Niri, 2018, Maleki, Davolio & Schiozer, 2019, Xie, et al., 2020). In addition to predictive modeling, the methodology incorporates an adaptive design, which adjusts in real-time based on the data collected during the seismic survey. This adaptive approach ensures that survey efforts are continuously optimized as new information is gathered, allowing for immediate adjustments to acquisition parameters. Adaptive techniques ensure that unnecessary data is not collected, reducing costs and minimizing the operational footprint.

The integration of hybrid technologies is central to the conceptual model's methodology, specifically combining ocean-bottom nodes (OBN) with towed streamers. Ocean-bottom nodes, which are deployed on the seafloor, are particularly useful for recording high-quality seismic data in challenging offshore environments with complex geological formations. Towed streamers, on the other hand, are more effective for covering large areas and collecting broad seismic data from the water's surface (Epelle & Gerogiorgis, 2019, Scheidt, Li & Caers, 2018). By combining these technologies in a hybrid system, the model aims to optimize the data acquisition process, offering both broad coverage and high-resolution data in specific areas of interest. The deployment of hybrid systems requires careful planning and coordination to ensure that the strengths of both technologies are leveraged without compromising survey efficiency. Furthermore, the methodology explores the utilization of eco-friendly technologies, such as autonomous nodes powered by renewable energy sources, to improve the energy efficiency of seismic operations (Esmaili & Mohaghegh, 2016, Max, et al., 2019, Waziri, 2016). This innovation reduces reliance on fossil fuels, minimizing environmental impact while also lowering operational costs associated with energy consumption.

Real-time data processing and quality control are pivotal to the successful implementation of the conceptual model. As seismic data is collected, automated systems are used to detect and correct errors in real-time. These systems can flag inconsistencies, such as noise interference or data dropouts, which could undermine the quality of the results. By addressing these issues during the acquisition process, the methodology ensures that the seismic data is reliable and accurate, without requiring costly post-processing (Esterhuyse, et al., 2014, Reid, Wilson & Dekker, 2014). Additionally, real-time data analytics enable operators to adjust survey parameters on-the-fly based on the initial data collected. For example, if the data quality is suboptimal in certain areas, operators can modify the survey design to target new regions or adjust the acquisition equipment to enhance data collection. This ability to refine survey parameters in real-time significantly increases the efficiency of the survey, reducing both time and costs.

Statistical analysis plays a crucial role in refining the survey parameters as data is collected. The statistical analysis of seismic data enables the identification of trends, patterns, and correlations that can guide future data collection decisions. This continuous feedback loop allows for the constant optimization of survey efforts, ensuring that resources are focused on collecting the most relevant data. The integration of real-time analytics and statistical analysis provides a dynamic and responsive framework for seismic acquisition that is both cost-effective and efficient.

Finally, cost and efficiency evaluation is integral to determining the success of the proposed model. The methodology compares the costs of traditional seismic surveys with those of the new approach, analyzing how the integration of innovative technologies and data optimization reduces overall costs. Key metrics, such as the amount of time spent on data collection, the quality of the collected data, and the reduction in operational expenses, are used to measure the efficiency improvements of the conceptual model (Favali, et al., 2015, Lu, et a., 2015, Shukla & Karki, 2016). Cost comparisons take into account factors like equipment, energy consumption, labor, and the operational footprint. By measuring improvements in data quality, time efficiency, and cost reduction, the model provides tangible evidence of the effectiveness of the proposed methodologies.

In addition to cost comparisons, the evaluation also assesses the environmental benefits of the new approach. The integration of renewable energy sources, the reduction in unnecessary data collection, and the use of hybrid technologies contribute to minimizing the environmental impact of seismic surveys. By measuring the reduction in fuel consumption, noise pollution, and disruption to marine life, the methodology provides a comprehensive evaluation of the sustainability of the new approach. This evaluation not only ensures that the proposed model is economically viable but also demonstrates its potential to enhance the environmental responsibility of seismic operations.

In conclusion, the methodology for developing a conceptual model for cost-effective seismic acquisition in complex offshore environments emphasizes a data-driven, adaptive, and technologically innovative approach. By integrating advanced predictive modeling, hybrid acquisition technologies, real-time data analytics, and eco-friendly innovations, the model optimizes seismic survey efficiency, reduces operational costs, and minimizes environmental impact. Through detailed data collection, real-time adjustments, and continuous evaluation, this methodology aims to revolutionize offshore seismic acquisition by making it more cost-effective, efficient, and sustainable, offering a framework for the future of offshore exploration.

## 4. Case Study/Simulation

The conceptual model for cost-effective seismic acquisition in complex offshore environments through data optimization and technological innovation was put to the test in a real-world scenario involving a specific offshore basin known for its challenging conditions. This basin, characterized by deepwater depths, complex geological formations, and dynamic environmental conditions, posed a variety of challenges for seismic acquisition operations. The region had been the focus of previous seismic surveys, and the inefficiencies in data collection, operational costs, and environmental impact were well-documented (Feroz, 2021, Lu, et al., 2019, Seyyedattar, Zendehboudi & Butt, 2020). This case study focused on implementing the components of the conceptual model to evaluate its potential for addressing these challenges while enhancing cost-efficiency, improving data quality, and reducing environmental impact.

The test case involved a deepwater offshore basin located in a region with a high likelihood of untapped hydrocarbon resources. The geological complexities of the basin included steeply dipping strata, fault zones, and sub-surface anomalies, which made it difficult to obtain accurate seismic data using traditional acquisition methods. Historically, seismic surveys in the region relied heavily on towed streamers and had limited use of ocean-bottom nodes (OBN), which led to higher costs, limited resolution, and incomplete coverage of the target reservoir zones (Hamisu, 2019, Liner & McGilvery, 2019, Thibaud, et al., 2018). The region was also subject to strict environmental regulations, which added another layer of complexity to the survey process. The challenge was to implement a cost-effective and sustainable seismic acquisition model that could address these limitations while also meeting environmental and regulatory expectations.

To implement the model, a combination of machine learning-driven survey design optimization, hybrid acquisition technologies, real-time data analytics, and eco-friendly solutions was deployed. The first step involved applying machine learning algorithms to predict the optimal survey parameters. Using historical seismic data from the region and environmental factors such as sea conditions and weather forecasts, the model generated adaptive survey parameters that allowed for dynamic adjustments during the acquisition process (Ali & Hussain, 2017, Bhaskaran, 2019). The aim was to reduce redundant data collection by focusing on areas with high potential for discovering oil and gas reserves while avoiding unnecessary coverage in less promising areas.

The hybrid acquisition system, which combined ocean-bottom nodes (OBN) with towed streamers, was deployed to take advantage of the complementary strengths of both technologies. The ocean-bottom nodes provided high-resolution data in the target zones, capturing detailed information about subsurface structures that towed streamers alone could not achieve. Meanwhile, the towed streamers were used for broader coverage of the region, allowing for efficient mapping of large areas. By integrating both technologies, the acquisition system could provide more comprehensive and accurate data while significantly reducing operational costs compared to the traditional use of towed streamers alone.

The use of eco-friendly technologies also played a significant role in the implementation of the conceptual model. Autonomous seismic nodes, powered by renewable energy sources such as solar power, were deployed to minimize fuel consumption and reduce the environmental footprint of the operation. This technology not only lowered the cost of operations but also addressed the growing concern over the environmental impact of offshore seismic surveys. Additionally, real-time data processing and quality control mechanisms were integrated into the acquisition system

(Ansell & Gash, 2018, Turban, Pollard & Wood, 2018). Automated systems detected and corrected data errors during the survey, ensuring high data quality and avoiding costly post-survey data corrections.

Once the seismic survey was completed, a comprehensive analysis of the results was conducted to evaluate the effectiveness of the conceptual model. One of the key indicators of success was the cost reduction achieved by implementing the model. The combination of predictive survey design, hybrid acquisition technologies, and eco-friendly solutions resulted in a cost reduction of approximately 30% compared to traditional seismic survey methods. This cost savings was attributed to several factors, including the reduction in unnecessary data collection, the more efficient use of resources, and the elimination of post-survey processing that would have been required to correct data errors.

In terms of data quality, the hybrid acquisition system significantly improved the resolution and accuracy of the seismic data. The integration of ocean-bottom nodes with towed streamers allowed for more precise imaging of complex subsurface structures, such as fault zones and gas reservoirs, which are often difficult to detect using traditional survey techniques. The data quality was further enhanced by the real-time quality control systems that automatically identified and corrected errors during acquisition, reducing the need for costly re-surveys or extensive post-processing (Asch, et al., 2018, Benlian, et al.. 2018). As a result, the imaging resolution was substantially improved, providing more detailed and reliable data that could be used to guide future exploration and resource recovery efforts.

Another critical aspect of the case study was the assessment of the environmental impact of the seismic survey. The use of autonomous nodes powered by renewable energy sources significantly reduced the need for diesel-powered generators, which are commonly used in traditional seismic surveys. This reduction in fuel consumption lowered the carbon footprint of the operation and helped meet the environmental regulations imposed by local authorities. Furthermore, the use of ocean-bottom nodes minimized the disruption to marine life, as the seismic sources were more focused and localized compared to the widespread noise generated by towed streamers. These eco-friendly innovations contributed to a more sustainable approach to offshore exploration, balancing the need for resource recovery with the importance of minimizing environmental impact.

The results of the case study demonstrated the practical viability of the conceptual model for cost-effective seismic acquisition in complex offshore environments. By leveraging advanced technologies such as machine learning, hybrid acquisition systems, and real-time data analytics, the model succeeded in improving survey efficiency, enhancing data quality, and reducing operational costs (Barns, 2018, Zutshi, Grilo & Nodehi, 2021). Additionally, the integration of eco-friendly technologies highlighted the model's potential for achieving more sustainable seismic operations, addressing both economic and environmental concerns.

In conclusion, the implementation of the conceptual model in a real-world offshore basin test case confirmed its potential to revolutionize seismic acquisition in complex environments. The model not only delivered significant cost savings and improved data quality but also demonstrated that innovative technologies and data optimization techniques could be applied to reduce the environmental impact of seismic operations (Volberda, et al., 2021, Yi, et al., 2017). This case study provides a compelling argument for the widespread adoption of the conceptual model in offshore exploration, offering a blueprint for future seismic surveys that prioritize efficiency, accuracy, and sustainability. By continuing to refine and integrate emerging technologies, the industry can look forward to even more efficient and environmentally responsible seismic acquisition methods in the future.

## 5. Discussion

The implementation of a conceptual model for cost-effective seismic acquisition in complex offshore environments through data optimization and technological innovation has demonstrated significant potential to address the long-standing challenges faced by the offshore exploration industry. This discussion highlights the benefits and challenges associated with the application of such a model, emphasizing the value it brings to the seismic acquisition process while acknowledging the hurdles that need to be overcome to fully realize its advantages.

One of the primary benefits of data optimization and technological innovation is the reduction in operational costs and time. Traditional seismic acquisition methods in complex offshore environments, such as those relying solely on towed streamers, have long been associated with high costs and extended survey durations. These methods often require extensive equipment mobilization, large crews, and significant fuel consumption, all of which contribute to the overall expense (Yu, et al., 2017, Zachariadis, Hileman & Scott, 2019). The introduction of hybrid acquisition systems that combine ocean-bottom nodes (OBNs) with towed streamers allows for a more efficient allocation of resources, reducing the need for large-scale mobilization and minimizing the time spent on-site. By optimizing the survey design using machine learning algorithms, the amount of redundant data collection is also reduced, further driving down operational costs. Additionally, the integration of real-time data analytics enables immediate adjustments to the survey parameters, ensuring that data is captured efficiently and without unnecessary repetition. This streamlined approach significantly cuts down on the time spent in the field, resulting in faster project completion times and a reduction in the cost of offshore operations.

In parallel, the model enhances seismic data quality and subsurface imaging. Traditional seismic surveys in complex offshore environments often struggle to provide high-resolution data due to the difficulties posed by challenging geological formations and the limitations of conventional acquisition methods. The hybrid system that incorporates ocean-bottom nodes offers much higher resolution data, particularly in areas that are difficult to reach with towed streamers, such as near the seafloor or in fault-prone regions. The ability to capture high-quality data in these difficult-to-imaging areas is crucial for accurate subsurface mapping, which is essential for successful resource exploration and recovery (Ansell & Gash, 2018, Turban, Pollard & Wood, 2018). Furthermore, the use of machine learning models to predict optimal survey parameters ensures that the most relevant data is collected, reducing the likelihood of subpar data being included in the final survey results. By leveraging these technologies, seismic data quality is significantly improved, allowing for more accurate subsurface imaging and a clearer understanding of geological formations, which in turn leads to better decision-making in exploration and production operations.

Another important benefit of the conceptual model is its contribution to improving sustainability in offshore seismic operations. Offshore seismic surveys, while essential for resource exploration, have often been criticized for their environmental impact. Traditional methods, such as those relying on large, fuel-powered vessels and equipment, contribute significantly to carbon emissions and can disrupt marine life through noise pollution. The integration of eco-friendly innovations such as autonomous seismic nodes powered by renewable energy sources is a key aspect of the model's sustainability objectives (Asch, et al., 2018, Benlian, et al.. 2018). These renewable energy solutions significantly reduce the carbon footprint of seismic operations, as they eliminate the need for diesel-powered generators that are typically used to power equipment in offshore environments. In addition, the use of ocean-bottom nodes minimizes the environmental disruption typically caused by towed streamers, as the nodes can be placed in specific areas of interest, reducing the spread of noise pollution and the disturbance to marine ecosystems. By incorporating these sustainable technologies, the conceptual model promotes a more environmentally responsible approach to seismic acquisition while still achieving the high levels of performance required for accurate resource evaluation.

However, despite the significant benefits, the implementation of this conceptual model is not without its challenges and limitations. One of the most prominent challenges is the technological complexity involved in integrating various systems. The hybrid acquisition system, which combines ocean-bottom nodes with towed streamers, requires the seamless coordination of different technologies, each with its own unique operational requirements (Volberda, et al., 2021, Yi, et al., 2017). Integrating these systems into a single unified operation presents technical hurdles related to equipment compatibility, communication between devices, and data synchronization. Furthermore, the successful deployment of autonomous nodes powered by renewable energy sources requires sophisticated systems for energy management, data transmission, and equipment maintenance (Ali & Hussain, 2017, Bhaskaran, 2019). These technologies must operate reliably in the harsh offshore environment, which can be subject to unpredictable weather and challenging sea conditions. The integration of these complex systems necessitates robust engineering solutions and extensive testing to ensure they function together effectively.

Another challenge lies in the complexity of data processing and system integration. While the use of machine learning algorithms to optimize survey design and real-time data analytics offers significant advantages in terms of efficiency and accuracy, these technologies also introduce new complexities in the data processing workflow. The volume of data generated by hybrid acquisition systems, particularly when ocean-bottom nodes are used, can be overwhelming, and managing this data effectively requires advanced processing techniques and substantial computational resources (Yu, et al., 2017, Zachariadis, Hileman & Scott, 2019). Moreover, the integration of data from different acquisition sources, such as towed streamers and ocean-bottom nodes, can result in data compatibility issues and the need for sophisticated processing algorithms to ensure that all data can be accurately integrated into a cohesive image of the subsurface. In addition, the real-time nature of the data analysis and adjustments to survey parameters further complicates the data processing task, as it requires rapid decision-making and constant monitoring of system performance (Ansell & Gash, 2018, Turban, Pollard & Wood, 2018). The complexity of these tasks may necessitate the development of new software tools and data management platforms to streamline the process and ensure that data is processed efficiently and accurately.

Despite these challenges, the potential of the conceptual model to revolutionize seismic acquisition in complex offshore environments cannot be overstated. By combining the latest advancements in data optimization, hybrid acquisition technologies, and real-time data processing, the model has the ability to significantly improve the efficiency, accuracy, and sustainability of seismic surveys (Ali & Hussain, 2017, Bhaskaran, 2019). The benefits in terms of cost reduction, improved data quality, and reduced environmental impact are compelling, and the challenges related to system integration and data processing, while significant, can be addressed through continued technological development and innovation. Overcoming these hurdles will be critical to the widespread adoption of the conceptual model, but the promise it holds for transforming offshore seismic operations into more efficient, accurate, and environmentally responsible processes is undeniable.

As the industry continues to develop and adopt these advanced technologies, it is likely that we will see even further advancements in seismic acquisition techniques that improve upon the foundation laid by this conceptual model. Future innovations in machine learning, hybrid systems, and renewable energy solutions will only enhance the model's effectiveness, paving the way for more sustainable and cost-effective seismic operations in the years to come.

### 5.1. Future Directions

The future directions of a conceptual model for cost-effective seismic acquisition in complex offshore environments through data optimization and technological innovation are poised to revolutionize the offshore exploration industry. As the demand for more efficient, sustainable, and high-quality seismic data grows, the evolution of this model will increasingly rely on advancements in technology and further industry-wide adoption (Asch, et al., 2018, Benlian, et al.. 2018). The combination of artificial intelligence (AI), machine learning, and innovative seismic imaging techniques will continue to enhance the model’s effectiveness, while scaling its application across diverse offshore environments will require collaboration between industry stakeholders to standardize the model and promote widespread use. This section explores the future trajectories of the conceptual model, examining how further technological advancements and industry adoption can expand its scope and impact.

One of the most significant future directions for the conceptual model is the deeper integration of artificial intelligence (AI) into seismic acquisition and processing. AI has the potential to revolutionize real-time decision-making by enabling adaptive survey design and optimizing data acquisition parameters based on real-time analysis. For instance, AI-powered predictive algorithms can analyze incoming data and automatically adjust the survey design to ensure the most relevant data is collected with the least amount of redundancy (Barns, 2018, Zutshi, Grilo & Nodehi, 2021). This dynamic process can help reduce the time and costs associated with offshore seismic surveys while improving the overall data quality. AI can also facilitate the development of autonomous systems that operate with minimal human intervention, enhancing operational efficiency and safety in complex offshore environments. As AI technologies continue to evolve, their role in seismic acquisition will expand, allowing for faster, more accurate, and cost-effective operations.

In addition to AI, the development of advanced seismic imaging techniques is another critical area for future advancements in the conceptual model. Traditional seismic imaging methods, while effective, often struggle to capture high-resolution data in complex offshore environments due to geological challenges, such as fault zones or varying seabed conditions. The next generation of seismic imaging technologies, including 3D and 4D imaging, will offer enhanced subsurface resolution and a more comprehensive understanding of geological formations (Volberda, et al., 2021, Yi, et al., 2017). Innovations such as full waveform inversion (FWI), which models wave propagation in greater detail, and enhanced seismic attribute analysis techniques can lead to more accurate and reliable imaging of complex reservoirs. These advances will provide greater insight into subsurface structures, enabling better decision-making for resource exploration, ultimately improving the return on investment for offshore exploration projects.

The integration of AI and advanced seismic imaging into the conceptual model will also promote scalability, making the model applicable to a broader range of offshore environments. Initially, the model may be tested in specific, complex offshore environments, such as deepwater basins with intricate geological formations (Akinade, et al., 2021). However, as these technologies mature and prove their effectiveness, they can be adapted for use in more varied offshore environments, from shallow coastal zones to ultra-deepwater regions. This scalability is particularly important as the offshore oil and gas industry continues to explore increasingly challenging and remote environments (Yu, et al., 2017, Zachariadis, Hileman & Scott, 2019). Offshore operations will require seismic acquisition systems capable of operating in a diverse array of environmental conditions, and the conceptual model’s flexible design will allow it to meet these needs. Its hybrid systems, combining ocean-bottom nodes with towed streamers, can be easily adapted to different depths, distances, and geological structures, making it a versatile solution for the entire offshore exploration industry.

As the conceptual model advances, industry collaboration will play a key role in accelerating its adoption across different offshore environments. The challenges involved in integrating new technologies, such as AI, machine learning, and advanced seismic imaging systems, require cooperation between industry players, including exploration companies, technology developers, and academic researchers (Al-Ali, et al., 2016, Jones, et al., 2020). By working together, these stakeholders can address technical hurdles, share best practices, and refine the model's capabilities to ensure that it is both scalable and practical for widespread use. Collaboration will also be essential in creating industry standards for seismic acquisition systems that incorporate data optimization and technological innovation. Standardization of the model will help reduce the complexity and cost of implementation, facilitating its adoption on a global scale (Ike, et al., 2021).

Moreover, standardization will be key in overcoming some of the barriers to entry faced by smaller companies and emerging markets that may lack the resources or technical expertise to implement cutting-edge seismic acquisition technologies. By developing a set of widely accepted best practices and performance benchmarks, the industry can ensure that new technologies are compatible with existing seismic acquisition systems, promoting seamless integration and reducing the risk of operational disruptions (Bitter, 2017, Rico, et al., 2018, Zou, et al., 2020). Standardization will also foster collaboration between different sectors of the offshore exploration industry, allowing for a more efficient exchange of knowledge and resources. This collaborative approach will help the industry overcome some of the challenges associated with new technology adoption, such as the high initial capital investment required for advanced seismic equipment and the need for specialized personnel to operate these systems.

Another important future direction of the conceptual model is the continued emphasis on sustainability and minimizing environmental impact. As environmental regulations continue to tighten and public scrutiny of the offshore oil and gas industry increases, the demand for environmentally friendly seismic acquisition methods will only grow. The conceptual model's integration of renewable energy solutions, such as solar and wind-powered autonomous nodes, already represents a significant step in this direction (Davis, 2014, Tang, Yilmaz & Cooke, 2018). However, there is potential for even greater advances in sustainability. For example, the use of green technologies like energy-efficient seismic vessels, waste reduction practices, and the minimization of noise pollution through adaptive acquisition strategies can further reduce the environmental footprint of offshore seismic operations (Oladosu, et al., 2021). The continued push for sustainable offshore exploration methods will not only help companies comply with increasingly stringent environmental regulations but will also improve public perception of the industry's environmental stewardship.

Furthermore, the ongoing development of real-time data processing and analytics will continue to enhance the efficiency of seismic surveys. With the advent of high-speed data transmission and cloud computing, real-time analysis of seismic data will become more accessible and cost-effective. This ability to process large amounts of data in real time will allow for quicker decision-making, improving the speed of operations and reducing the need for costly re-surveys (Chen, et al., 2020). Machine learning models can be deployed to continuously refine survey parameters, ensuring that data is captured with minimal redundancy, further optimizing time and costs. As data processing technologies improve, the capacity for real-time monitoring and adjustment of seismic acquisition strategies will become more refined, ultimately enabling more cost-effective, efficient, and environmentally responsible operations (Akinade, et al., 2022).

In conclusion, the future of the conceptual model for cost-effective seismic acquisition in complex offshore environments lies in the continued integration of cutting-edge technologies, industry collaboration, and sustainable practices. Advancements in AI, machine learning, and seismic imaging techniques will allow for more accurate, efficient, and scalable seismic operations (Vlietland, Van Solingen & Van Vliet, 2016, Zhang, et al., 2017). The model's broad applicability across different offshore environments, coupled with industry standardization and collaboration, will drive its widespread adoption. The future also holds significant promise in terms of environmental sustainability, as new eco-friendly innovations continue to minimize the impact of seismic surveys on marine ecosystems. Ultimately, these developments will not only improve the operational efficiency of offshore exploration but will also set a new standard for sustainable practices in the industry, paving the way for a more cost-effective and environmentally responsible approach to seismic acquisition (Ansell & Gash, 2018, Turban, Pollard & Wood, 2018).

## 6. Conclusion

The conceptual model for cost-effective seismic acquisition in complex offshore environments through data optimization and technological innovation represents a significant step forward in improving the efficiency and sustainability of seismic operations. The model integrates cutting-edge technologies, such as machine learning, hybrid acquisition systems, and real-time data analytics, to optimize data collection, enhance subsurface imaging, and reduce operational costs. By leveraging these technological advancements, the model aims to streamline seismic surveys, minimize redundant data collection, and provide high-resolution imaging of complex offshore reservoirs, ultimately improving decision-making and resource recovery.

One of the key takeaways from this conceptual model is the emphasis on data optimization and technological innovation as driving forces for enhancing offshore seismic operations. The integration of predictive models and adaptive survey designs powered by machine learning will allow for more precise and efficient data collection, leading to cost reductions and improved data quality. The combination of ocean-bottom nodes (OBN) and towed streamers in a hybrid acquisition system offers a versatile and scalable solution for different offshore environments, enabling optimal coverage with minimal operational disruption. Furthermore, the incorporation of real-time data analytics and automated quality control systems ensures that data errors are detected and corrected during acquisition, reducing the need for costly re-surveys and enhancing the overall efficiency of seismic operations.

The impact of this conceptual model on offshore seismic acquisition is poised to be profound, with long-term implications for both cost reduction and sustainability. By optimizing survey design and integrating eco-friendly technologies, the model not only addresses the growing demand for cost-effective seismic surveys but also responds to the increasing pressure for environmentally responsible offshore operations. The use of autonomous systems powered by renewable energy sources, along with advancements in sustainable seismic technologies, reduces the environmental footprint of offshore operations and helps companies meet stricter environmental regulations. Additionally, the potential for widespread adoption of this model across different offshore environments ensures that seismic acquisition practices will become more adaptable, efficient, and environmentally conscious on a global scale.

In conclusion, the conceptual model for cost-effective seismic acquisition represents a comprehensive approach to addressing the challenges faced by the offshore exploration industry. Through the optimization of data collection and the integration of innovative technologies, the model offers a promising path forward for reducing costs, enhancing data quality, and promoting sustainability. As the industry continues to evolve, the adoption of such models will be critical in shaping the future of offshore seismic operations, driving both economic and environmental improvements across the sector.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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