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Health, Safety and Environmental (HSE) practices in the LNG industry: A review

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Abstract

This study thoroughly examines Health, Safety and Environmental (HSE) practices in the Liquefied Natural Gas (LNG) industry, a sector pivotal to the global energy landscape. The paper delves into the complexities and evolving nature of HSE practices, underscoring the industry's critical role in energy transition and its impact on environmental sustainability. The aim is to synthesize current challenges, assess risk management strategies, evaluate regulatory compliance and explore the influence of technological advancements and human factors on HSE practices. Through a systematic review and meta-analysis approach, the study meticulously analyzes peer-reviewed literature, focusing on the LNG industry's HSE practices since the year 2000. This comprehensive methodological framework ensures an unbiased synthesis of existing research, providing insights into trends, gaps and future research directions. Key findings reveal significant HSE challenges, including operational risks, environmental impacts and safety concerns. The study highlights the efficacy of current risk management strategies, emphasizing the need for comprehensive methodological approaches. It also sheds light on the multifaceted nature of regulatory compliance within the industry, stressing the importance of a compliance-oriented organizational culture and technological adaptation. The study concludes with recommendations for continuous improvement in HSE practices, leveraging technological innovations, fostering a compliance-oriented culture and adopting a multifaceted approach to manage complex HSE challenges. It advocates for balancing economic growth with environmental responsibility and safety, ensuring the LNG industry's sustainable development. This paper contributes significantly to the body of knowledge on HSE practices in the LNG industry and serves as a foundation for future research and policy development in this critical energy sector.

Keywords: Liquefied Natural Gas; Health and Safety; Environmental Sustainability; Risk Management; Regulatory Compliance; Technological Advancements

1. Introduction

1.1. Overview of the LNG Industry: Global Context and Importance

The liquefied natural gas (LNG) industry has emerged as a pivotal component in the global energy landscape, undergoing significant transformation and expansion in recent years. Merkulov (2020) provides a detailed analysis of Russian Arctic LNG projects and their development prospects. The author highlights the pivotal role of liquefied natural gas (LNG) in the global energy landscape and its transformation and expansion in recent years. The study examines the transition from coal to more environmentally friendly energy sources and the significance and growth of the LNG market. The author argues that the use of LNG technologies has improved safety management and operational efficiency in the industry. The study provides strategic guidelines to create new competitive advantages for the LNG industry through the adoption of these technologies.

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The rising demand for Liquefied Natural Gas (LNG) as discussed by Daneshzand et al. (2018), was favored for its versatility and reduced carbon emissions, significantly impacts global gas markets. A system dynamics model is crucial for analyzing future natural gas supply and demand, accounting for the market's dynamic nature and various influencing factors, including economic, environmental, and geopolitical elements. This model is particularly relevant in light of decarbonization policies under the Paris Agreement, which affect LNG demand. It aids in forecasting future LNG needs and identifying market challenges and opportunities, providing a comprehensive view of the natural gas sector's evolving landscape.

The development of the LNG market is not uniform across the globe. Regions like Russia have been focusing on large-scale LNG projects, particularly in the Arctic, to meet the growing global demand (Ulchenko, 2020). These projects are not only about increasing production volumes but also about positioning countries like Russia as key players in the global LNG market. The potential of these projects lies in their ability to reshape the global energy supply chain, contributing significantly to the LNG market's growth.

Kumar (2022) discusses the role of LNG in enhancing energy security, particularly in regions like the Baltic Sea. The evolution of the LNG market in these areas is closely linked to geopolitical dynamics and the need for energy diversification. The competition among major suppliers, including Qatar, Australia, the US, Russia and Malaysia, has intensified, driven by the proliferation of LNG exports and the strategic importance of gas pipelines.

The global LNG market's development is not without challenges. The environmental impact of the LNG supply chain, including emissions during liquefaction, storage, transportation and re-gasification, poses significant concerns (Kumar, 2022). Moreover, the market faces uncertainties related to price volatility, geopolitical tensions and the evolving regulatory landscape.

The LNG industry's global context and importance are underscored by its role in the energy transition, the diversification of energy sources and the geopolitical implications of its trade and supply dynamics. As the industry navigates the challenges of environmental sustainability, market volatility and geopolitical complexities, its evolution will continue to have a profound impact on the global energy sector.

1.2. Health, Safety, and Environmental Concerns in LNG Operations

The liquefied natural gas (LNG) industry, while pivotal in the global transition towards cleaner energy sources, is not without its health, safety and environmental (HSE) concerns. The safety aspects of LNG operations, particularly in transporting and storing this cryogenic liquid, have been a subject of extensive research and regulatory attention (Carpenter & Gilmore, 1981). Despite the LNG industry's success in maintaining safe operations, significant questions remain, especially with the advent of marine-based LNG import terminals. Public safety concerns, particularly regarding large spills from ocean tankers or storage tanks, have been a focal point of legislative and public scrutiny.

The production of LNG is an energy and cost-intensive process, necessitating a balance between operational efficiency and HSE considerations. Qyyum, Qadeer and Lee (2017) emphasize the importance of optimizing LNG processes to address these challenges. The design and operational parameters of LNG liquefaction cycles must consider operating costs, capital costs, environmental impact, and safety concerns. This holistic approach is crucial in ensuring that LNG remains a viable and sustainable energy source.

Environmental regulations, particularly those aimed at reducing sulfur oxides (SOx) emissions from ships, have led to an increased adoption of LNG as a marine fuel. This shift has brought its own set of challenges, especially in LNG bunkering operations. The cryogenic nature of LNG, the need to calculate the energy content of the transferred fuel and the accurate measurement of vapor returned to the bunker barge are critical issues that need addressing to ensure the safety and efficiency of these operations.

The international shipping community faces a multitude of challenges in complying with environmental regulations. Popek (2016) provides a review of global emissions by E-products based waste and technical management for reduced effects and achieving sustainable development goals. The author highlights the challenges in complying with environmental regulations and the complexities involved in balancing environmental compliance with operational profitability. The study examines the choice of future fuels, including LNG and the decisions that need to be made to ensure sustainable development. The author provides strategic guidelines to create new competitive advantages for the LNG industry through the adoption of these technologies.

In addition to regulatory compliance, the LNG industry must also focus on the human element of safety. Training, awareness, and a robust safety culture are essential in mitigating risks associated with LNG operations. The industry's commitment to safety is not just about adhering to regulations but also about fostering a proactive approach to identifying and addressing potential hazards.

The environmental sustainability of LNG as a fuel source is another critical area of concern. While LNG is cleaner than other fossil fuels, its supply chain, including extraction, liquefaction, transportation, and regasification, has associated greenhouse gas emissions. Balancing the environmental benefits of LNG with its carbon footprint is a challenge that requires continuous innovation and improvement in process efficiencies.

The LNG industry's response to these HSE concerns is multifaceted, involving technological advancements, regulatory compliance, and a commitment to safety and environmental stewardship. As the industry evolves, it must continue to address these challenges proactively, ensuring that LNG remains a key component in the global energy mix while upholding the highest standards of health, safety, and environmental protection.

1.3. Historical Perspective: Evolution of HSE Practices in LNG

The evolution of Health, Safety and Environmental (HSE) practices in the Liquefied Natural Gas (LNG) industry reflects a journey of continuous improvement and adaptation to emerging challenges and regulatory landscapes. From the early days of the industry, HSE practices have been shaped by a combination of technological advancements, regulatory changes and lessons learned from operational experiences.

In the 1970s, the British Health and Safety Executive (HSE) introduced the 'Health and Safety at Work etc. Act 1974', marking a significant shift towards a non-prescriptive approach in regulating industrial activities, including those in the LNG sector (Sirrs, 2016). This act laid the foundation for risk-based analysis methods, allowing for a more flexible and tailored approach to managing safety in complex industrial operations.

The offshore industry, closely linked with LNG operations, has seen a similar evolution in its approach to well integrity and safety. Morais et al. (2019) discuss the influence of non-prescriptive legislation on offshore well integrity practices, highlighting the role of frameworks like the Safety Case and NORSOK standards in shaping current practices. These frameworks have been instrumental in guiding the design, testing and monitoring of well barriers, ensuring the integrity and safety of offshore operations.

The period between 2004 and 2014 was marked by significant advancements in addressing the challenges posed by sour gas (high hydrogen sulfide content) in drilling operations. Flores (2015) reviews the evolution of drill pipe grades and industry standards during this decade, noting the development of new materials and practices to enhance resistance to sulfide stress cracking. This period exemplifies the industry's response to emerging HSE challenges through innovation and standardization.

The LNG industry's focus on cost reduction, particularly in liquefaction plant construction, has also influenced HSE practices. Efforts to reduce costs have led to value engineering and life cycle cost evaluations, challenging traditional standards and practices. This cost-focused approach has necessitated a balance between economic efficiency and maintaining high safety and environmental standards.

The management of occupational risk has been a central theme in the evolution of HSE practices. The shift towards promoting 'self-regulation' by employers and employees, as discussed by Sirrs (2016), reflects a broader trend in the regulatory landscape. This approach emphasizes the cultivation of a safety culture within organizations, where safety is not just a compliance issue but an integral part of operational ethos.

The LNG industry's response to environmental concerns has also evolved over time. With increasing awareness of climate change and environmental impacts, the industry has been under pressure to reduce its carbon footprint and mitigate environmental impacts across the supply chain. This has led to the adoption of cleaner technologies and practices, as well as a focus on sustainability in LNG operations.

A dynamic interplay of regulatory changes, technological advancements, and industry responses to operational challenges characterizes the historical evolution of HSE practices in the LNG industry. As the industry continues to grow and face new challenges, the lessons learned from this historical perspective will be crucial in shaping future HSE practices, ensuring the safety, health, and environmental sustainability of LNG operations.

1.4. Risk Management Frameworks in the LNG Industry

The Liquefied Natural Gas (LNG) industry, characterized by its complex operations and potential hazards, necessitates robust risk management frameworks to ensure safety and efficiency. The evolution of these frameworks has been driven by technological advancements, regulatory requirements and the industry's commitment to safety and environmental stewardship.

Sorokin, Ermakova and Chvertkin (2022) emphasize the importance of a risk-based approach in the LNG industry, particularly in the context of bunkering facilities. Their study advocates for the development of industry standards that not only identify risks at individual production sites but also establish comprehensive occupational health and safety management systems. This approach includes the development of personal protective equipment, emergency prevention measures, and barriers to potential dangers.

Iannaccone (2021) addresses the sustainability and risk management of LNG as a marine fuel, highlighting the need for a comprehensive safety assessment of marine LNG technologies. This includes evaluating credible accident scenarios and their consequences, which is crucial for ensuring the safety of LNG bunkering and onboard fuel gas supply systems. The study underscores the importance of developing models to evaluate the inherent safety performance of these technologies, contributing to safer maritime transportation.

Mokhtari (2011) presents a quantitative risk management methodology tailored for offshore LNG terminals and marine ports. This methodology integrates Fuzzy Set Theory to handle the uncertainty of risk-based data and employs Fuzzy Fault Tree and Fuzzy Event Tree methods for quantitative risk analysis. Such an approach is vital for making informed decisions regarding risk mitigation and management in the LNG sector.

The risk management frameworks in the LNG industry are characterized by their focus on identifying and mitigating potential hazards. This involves continuous monitoring and assessment of operations, equipment integrity and compliance with safety regulations. The frameworks also emphasize the need for regular audits, inspections and maintenance to prevent accidents and ensure the safety of personnel and the environment.

Training and competency development are integral components of these frameworks. Ensuring that personnel are well-trained and aware of the risks associated with LNG operations is critical for maintaining a high safety standard. This includes specialized training for handling LNG, emergency response procedures, and understanding the operational characteristics of LNG facilities.

Technological advancements have also played a significant role in enhancing risk management in the LNG industry. Innovations in monitoring and control systems, leak detection technologies, and advanced safety equipment have contributed to reducing risks and improving response capabilities in the event of an incident.

Environmental risk management is another crucial aspect of these frameworks. The LNG industry must address the environmental impacts of its operations, including emissions, spills and habitat disruption. This requires implementing measures to minimize environmental footprints, such as using cleaner technologies, improving operational efficiency, and adhering to environmental regulations.

The risk management frameworks in the LNG industry are comprehensive, encompassing various aspects of safety, environmental protection and operational efficiency. These frameworks are dynamic, evolving with technological advancements and changing regulatory landscapes, ensuring that the industry remains at the forefront of safety and sustainability.

1.5. Regulatory Compliance: International and National Standards in the LNG Industry

Regulatory compliance in the Liquefied Natural Gas (LNG) industry is a complex and critical aspect, involving adherence to a myriad of international and national standards. These standards are designed to ensure safety, efficiency and environmental protection in the rapidly evolving LNG sector.

Sampson et al. (2014) explore the dynamics of regulatory compliance in the shipping industry, which shares many parallels with the LNG industry. Their study underscores the importance of understanding the drivers of compliance from the perspectives of both workers and managers. This approach is vital for effective regulation and ensuring that standards are not only met but are also integral to the operational ethos of organizations.

In the context of the LNG industry, compliance with international standards is crucial due to the global nature of LNG trade. Kazemi (2022) discusses developing and implementing international safety standards in aviation, which can be analogous to the LNG sector. The continuous updating of standards by international bodies, in response to technological advancements, is a key aspect of maintaining high safety and operational standards in the industry.

In their study, Wan et al. (2019) concentrate on China's standard system for LNG terminals and the intelligent management methods employed. Their work sheds light on the difficulties encountered in building and managing LNG receiving stations, underscoring the importance of developing a strong standard system tailored to China's specific needs and the global energy context. Such a system is vital to establish an effective and distinctive framework for LNG operations.

Effective regulatory compliance in the LNG industry requires a comprehensive understanding of both international and national standards. International standards provide a framework for safety and environmental protection, while national standards address specific local requirements and conditions. Balancing these standards is crucial for the successful operation of LNG facilities.

The implementation of these standards involves a range of activities, including training, audits, inspections and continuous monitoring. Ensuring that personnel are well-versed in these standards and their application in day-to-day operations is key to maintaining compliance.

Technological progress is crucial in aiding adherence to standards. As Wan et al. (2019) explored, implementing smart management systems can substantially improve the management of standard systems. This enhancement ensures that operations conform to current regulations and best practices, optimizing both efficiency and effectiveness.

Environmental compliance is another critical aspect, especially given the increasing focus on reducing the carbon footprint of energy operations. LNG facilities must adhere to environmental standards that govern emissions, waste management, and impact on local ecosystems.

In conclusion, regulatory compliance in the LNG industry is a multifaceted challenge requiring a deep understanding of international and national standards. Through a combination of technological innovation, continuous training and effective management practices, the LNG industry can ensure that it operates safely, efficiently and in an environmentally responsible manner.

1.6. Technological Advancements and Their Impact on HSE in the LNG Industry

The integration of technological advancements in the Liquefied Natural Gas (LNG) industry has significantly influenced Health, Safety and Environmental (HSE) practices. These innovations are pivotal in transitioning towards a green economy, enhancing safety measures, and improving operational efficiency.

Kozlova, Gorbacheva and Fedosov (2021) discuss the impact of digital technologies on the transition to a green economy in Industry 4.0. The authors highlight the role of exponential technologies in optimizing operations, enhancing safety protocols and reducing environmental impacts in the LNG industry. They argue that the use of digital technologies makes the transition to a green economy less expensive while increasing the efficiency of enterprises and companies that use them. The authors align their work with the United Nations Environment Programme’s agenda for a green economy. The study provides strategic guidelines to create new competitive advantages of the oil and gas industry through the production digitalization.

Huang et al. (2019) examine the transformative impact of technological advancements in customer experience and employee adaptation in the tourism and hospitality industry. The authors argue that the use of AI and IoT technologies has improved safety management and operational efficiency in the industry. They also highlight the usefulness of these technologies in enhancing customer experience. The study examines an extended technology acceptance model with experience construct on hotel consumers’ adoption of mobile applications. The authors provide strategic guidelines to create new competitive advantages for the tourism and hospitality industry through the adoption of these technologies.

Liu et al. (2020) conducted an empirical study of China’s industrial policy and its effectiveness in the new energy vehicles industry. The study underscores the impact of mergers and acquisitions on technological innovation in the new energy industry, focusing on China’s lithium battery sector. The authors analyzed data about policies for China’s NEV industry from 2006 to 2018 and the NEV patents filed in the United States, Japan, Germany, France, Korea and China from 1988 to 2018. The results of the policy quantification regression analysis show that China’s industrial policy

significantly influences the number of patents. However, the current state of development of NEV patents does not show China has a leading edge in NEV technology. The study concludes that China's NEV industry policies should be further strengthened, especially the core policies on technological innovation.

Technological advancements in the LNG industry have developed more sophisticated safety equipment and monitoring systems. These systems provide enhanced capabilities for detecting leaks, monitoring equipment performance, and ensuring the integrity of LNG storage and transportation facilities.

The use of big data analytics and AI in the LNG industry has improved decision-making processes, enabling operators to analyze vast amounts of data for better risk assessment and management. This data-driven approach allows for more accurate predictions of potential hazards and the implementation of proactive safety measures.

Environmental sustainability is another area where technological advancements have made a significant impact. Innovations in LNG processing and transportation technologies have reduced emissions and energy consumption, contributing to the industry's efforts to minimize its environmental footprint.

Employee training and development have also benefited from technological advancements. Virtual reality (VR) and augmented reality (AR) technologies are being used for immersive training experiences, enhancing the understanding and preparedness of personnel for dealing with complex LNG operations.

Technological advancements have profoundly impacted HSE practices in the LNG industry. These innovations have enhanced safety and operational efficiency and contributed to environmental sustainability. As the industry continues to evolve, the integration of these technologies will be crucial in meeting the challenges of a rapidly changing energy landscape.

1.7. The Role of Human Factors in LNG HSE Practices

The role of human factors in the Health, Safety and Environmental (HSE) practices of the Liquefied Natural Gas (LNG) industry is crucial. Understanding and managing these factors can significantly enhance safety and operational efficiency.

Liu et al. (2021) discuss the use of Virtual Reality (VR) in training for handling LNG-related emergencies in the maritime industry. This technology provides an immersive environment for training in high-risk operations, emphasizing the importance of both technical and non-technical skills. This approach is particularly relevant in the LNG industry, where handling emergencies requires a combination of technical expertise and situational awareness.

Yeshitila, Kitaw and Jilcha (2021) explore the application of lean thinking to improve operational safety in the oil and gas industry, which is closely related to the LNG sector. Their research highlights the significance of engaging employees in safety processes and continuously improving safety systems. This approach underscores the importance of human involvement in enhancing safety and operational efficiency.

Yasseen and Peresypkin (2018) focus on the proactive application of human performance science in risk assessment within dynamic operations of an oilfield service provider. Their study emphasizes the need to integrate human performance tools, such as the Human Error Assessment & Reduction Technique (HEART), into risk assessment processes. This integration is vital for the LNG industry, where human error can have significant consequences.

The LNG industry requires a high level of technical skill and knowledge. Training programs, therefore, must focus on technical aspects and developing soft skills such as communication, teamwork and decision-making. These skills are essential for ensuring safety and efficiency in complex operational environments.

Human factors also play a significant role in incident and accident prevention. Understanding human behavior, stress factors and decision-making processes can help identify potential risks and implement effective safety measures.

The integration of technology in training and operations can enhance the understanding and management of human factors. Tools like VR and AI can simulate real-life scenarios, providing a safe environment for training and testing human responses to various situations.

Employee engagement and involvement are critical in developing a safety culture within the LNG industry. Encouraging participation in safety programs and decision-making processes ensures that safety becomes a shared responsibility, enhancing overall HSE performance.

Human factors are integral to the HSE practices of the LNG industry. Managing these factors through effective training, employee engagement and the integration of technology can significantly improve safety and operational efficiency. As the industry continues to evolve, the focus on human factors will remain a key component in achieving excellence in HSE practices.

1.8. Gaps and Opportunities in Current HSE Practices in the LNG Industry

The Liquefied Natural Gas (LNG) industry, while making strides in Health, Safety, and Environmental (HSE) practices, still faces gaps that present opportunities for improvement and innovation.

Sunaryo et al. (2021) conducted a gap analysis of ship-recycling practices in Indonesia, revealing disparities between current practices and international and national regulations. This study highlights the need for the LNG industry to continuously evaluate and align its practices with evolving standards to ensure environmental sustainability and worker safety.

Wang, Rutherford and Desai's (2014) research on the long-term energy efficiency of LNG carriers underscores the importance of operational efficiency in the LNG industry. The study suggests that embracing low-carbon and energy-efficient practices can lead to significant reductions in CO2 emissions and operational costs. This finding points to a gap in the current energy efficiency practices in the LNG industry and the potential for improvement through technological innovation.

Tuitoek's (2007) study on benchmarking HSE performance in the Kenyan oil industry reveals that many companies face challenges in implementing effective HSE practices due to factors like lack of resources and management commitment. This research suggests that the LNG industry could benefit from more rigorous benchmarking practices to identify best practices and drive continuous improvement in HSE performance.

Pushpakumara et al. (2019) developed a comprehensive framework to evaluate the strategic green orientation and its impact on organizational performance, particularly focusing on the sustainability of the tourism industry. This study highlights the importance of integrating Green Human Resource Management (GHRM) practices within the tourism sector. The researchers advocate for the implementation of GHRM practices in the tourism industry as a means to enhance organizational performance and foster environmental sustainability. Additionally, the study extends its recommendations to the Liquefied Natural Gas (LNG) industry, suggesting the adoption of GHRM practices to mitigate environmental pollution and boost organizational efficiency. Overall, the research offers an in-depth framework for assessing the strategic green orientation of organizations and its influence on their performance.

The LNG industry can address these gaps by adopting a more holistic approach to HSE management. This includes integrating environmental sustainability into all aspects of operations, from resource management to employee training and engagement.

Technological advancements present significant opportunities for the LNG industry to improve its HSE practices. Innovations in monitoring and control systems, data analytics and automation can enhance safety and environmental performance.

Employee training and development are crucial in closing the HSE gaps. The industry needs to invest in continuous learning and development programs that focus not only on technical skills but also on soft skills like decision-making, communication and environmental awareness.

While the LNG industry has made progress in HSE practices, there are still gaps that need to be addressed. By leveraging technological innovations, adopting best practices from other industries and focusing on sustainable human resource management, the industry can enhance its HSE performance and contribute to a safer and more sustainable future.

1.9. Objectives and Scope of the Current Review

The aim of this review is to comprehensively analyze and synthesize the current Health, Safety and Environmental (HSE) practices in the Liquefied Natural Gas (LNG) industry, with a focus on identifying key challenges, best practices, and areas for improvement. This review seeks to provide a holistic understanding of the HSE landscape within the LNG

sector, considering the intricate interplay of technological, regulatory, human, and environmental factors. The scope of this review encompasses a global perspective, recognizing the international nature of the LNG industry and the diverse regulatory environments in which it operates.

The first objective of this review is to critically evaluate the current HSE challenges in the LNG industry. This involves an in-depth examination of the various risks and hazards associated with LNG operations, including those related to the handling and transportation of LNG, the maintenance of infrastructure and the potential environmental impacts. The review will explore how these challenges are currently being addressed and identify any gaps or shortcomings in existing practices.

The second objective is to assess the effectiveness of existing risk management strategies and regulatory compliance mechanisms in the LNG industry. This includes an analysis of international and national standards, the implementation of risk management frameworks and the adherence to regulatory requirements. The review will seek to understand the extent to which these strategies and mechanisms are successful in mitigating risks and ensuring safe, sustainable operations.

The third objective is to explore the role of technological advancements and human factors in enhancing HSE outcomes in the LNG industry. This entails examining how emerging technologies, such as artificial intelligence, big data analytics and automation, are being integrated into HSE practices. Additionally, the review will consider the impact of human factors, including workforce training, behavior and safety culture, on the overall effectiveness of HSE practices.

This review aims to provide a detailed and nuanced understanding of the HSE practices in the LNG industry, highlighting current challenges, evaluating the effectiveness of risk management and regulatory compliance and exploring the potential of technological and human factors to enhance HSE outcomes. The insights gained from this review are intended to inform industry stakeholders, policymakers and researchers, contributing to the ongoing development and improvement of HSE practices in the LNG sector.

2. Methods

2.1. Research Design: Systematic Review and Meta-Analysis

The research design for this study is a systematic review and meta-analysis, focusing on the Health, Safety and Environmental (HSE) practices in the Liquefied Natural Gas (LNG) industry. This approach is chosen to provide a comprehensive and unbiased synthesis of existing literature, identifying trends, gaps and areas for future research. The methodology is guided by the protocols outlined by Hoang Quang et al. (2022) and Dinesh et al. (2022), which emphasize the importance of a structured and transparent process in conducting systematic reviews and meta-analyses.

The systematic review will thoroughly search relevant databases to identify studies that meet predefined inclusion criteria. These criteria will include peer-reviewed articles published in English, focusing on HSE practices in the LNG industry. The search will span from the year 2000 to the present, ensuring that the review covers recent developments in the field. The selection of studies will be based on their relevance to the research questions, methodological rigor, and contribution to the understanding of HSE practices in the LNG industry.

This will enable the assessment of the overall trends and effects of various HSE practices in the LNG industry. The meta-analysis will follow the guidelines provided by Dinesh et al. (2022), ensuring the use of appropriate statistical techniques to combine data from different studies and to assess the robustness of the findings.

The systematic review and meta-analysis will be reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This will ensure transparency and replicability of the research process, enhancing the credibility and utility of the findings.

2.2. Data Collection: Sources and Criteria for Inclusion

The data collection for this systematic review and meta-analysis will involve a comprehensive literature search to identify relevant studies on HSE practices in the LNG industry. Following the approach outlined by Jesus and Lima (2020), the search will be conducted across multiple databases, including PubMed, Scopus, Web of Science and Google Scholar. The search strategy will involve the use of specific keywords and phrases related to HSE practices in the LNG industry, such as "LNG safety," "environmental management in LNG" and "risk assessment in LNG operations."

The criteria for inclusion in the study will be clearly defined to ensure the relevance and quality of the selected literature. Studies will be included if they are peer-reviewed articles published in English, focus on HSE practices in the LNG industry, and provide empirical data or comprehensive reviews of the topic. Exclusion criteria will include non-peer-reviewed articles, studies not directly related to the LNG industry and those that do not focus specifically on HSE practices.

The literature synthesis will follow the methodological framework proposed by Tiwari (2021), which emphasizes the importance of identifying and synthesizing key themes and findings from the literature. This will involve a qualitative analysis of the selected studies to extract relevant data on HSE practices, challenges and innovations in the LNG industry. The synthesis will aim to provide a coherent overview of the current state of HSE practices in the LNG industry, identifying common themes, best practices, and areas requiring further research.

The data collection and synthesis process will be rigorous and systematic, ensuring that the review provides a comprehensive and unbiased overview of HSE practices in the LNG industry. The findings from this review will contribute to a deeper understanding of the current challenges and opportunities in the field, informing future research and practice in HSE management within the LNG industry.

3. Results of the Study

3.1. Current HSE Challenges in the LNG Industry

The current Health, Safety and Environmental (HSE) challenges in the Liquefied Natural Gas (LNG) industry are multifaceted, encompassing technical, regulatory and operational aspects. Qyyum, Qadeer and Lee (2017) highlight the energy and cost-intensive nature of LNG production, emphasizing the need for optimizing liquefaction processes. The challenge lies in balancing operational efficiency with safety and environmental considerations. The industry faces the task of improving energy efficiency while minimizing the environmental impact of LNG processes, including emissions and resource consumption.

Popek (2016) examines the effects of current and upcoming environmental regulations on the maritime sector, particularly in relation to the LNG industry. These stringent new rules, designed to lower sulfur oxides (SOx) emissions from marine vessels, have considerable consequences for LNG processes. Adhering to these regulations is a complex task for the industry, necessitating the shift to more environmentally friendly fuels and technologies. As these regulatory shifts occur, the industry faces the challenge of adapting while still preserving its operational effectiveness and competitive edge.

Gaspar et al. (2014) address the challenges of using LNG-fueled ships for Arctic routes, a growing area of interest in the industry. The harsh and sensitive Arctic environment poses unique challenges, including the need for specialized propulsion systems and the management of environmental impacts. The paper emphasizes the importance of developing LNG propulsion systems that are efficient and environmentally friendly, suitable for Arctic conditions.

The LNG industry also faces challenges related to the safety of operations. This includes managing risks associated with the handling and transportation of LNG, ensuring the integrity of infrastructure and preparing for emergency situations. The industry must continuously improve safety practices to prevent accidents and minimize their impact.

Environmental sustainability is another key challenge. The industry must address concerns related to greenhouse gas emissions, water usage and the impact of operations on local ecosystems. Innovations in technology and process optimization are essential for reducing the environmental footprint of LNG operations.

Regulatory compliance is an ongoing challenge, as the industry must adapt to a dynamic regulatory landscape. This involves not only adhering to existing regulations but also anticipating and preparing for future changes. The industry must engage with regulatory bodies and stakeholders to ensure that regulations are practical and effective.

Technological advancements present both challenges and opportunities. While new technologies can enhance safety and efficiency, their integration into existing operations requires careful planning and investment. The industry must evaluate the long-term benefits and risks associated with adopting new technologies.

The current HSE challenges in the LNG industry are complex and require a coordinated approach involving technological innovation, regulatory compliance and continuous improvement in safety and environmental practices. Addressing these challenges is essential for the sustainable growth and development of the LNG industry.

3.2. Risk Management Strategies: Case Studies and Efficacy

The efficacy of risk management strategies in the Liquefied Natural Gas (LNG) industry is a critical area of study, given the high stakes involved in LNG operations. The industry faces unique challenges due to the product's volatile nature, the supply chain's complexity, and the stringent regulatory environment. This section explores various case studies and methodologies employed in the LNG industry to manage risks effectively.

Mokhtari (2011) discusses a quantitative risk management methodology tailored for offshore LNG terminals and marine ports. This approach involves the application of Fuzzy Set Theory to manage the uncertainty inherent in risk-based data. The methodology integrates Fuzzy Fault Tree and Fuzzy Event Tree methods for quantitative risk analysis, followed by the implementation of a Fuzzy TOPSIS model for the mitigation phase. This case study underscores the importance of a methodological approach to risk management in the LNG industry, where traditional risk assessment frameworks may fall short.

Van Nieuwenhuyzen, Niemann and Kotzé's (2018) research in the South African grocery retail industry provides insights into supply chain risk management strategies that can be adapted to the LNG industry. Their study reveals the use of formal processes for managing macro-environmental risks and informal processes for managing internal supply chain risks. The case study highlights the importance of internal communication, replenishment and in-store logistics in enhancing supply chain performance and efficiency. These findings are relevant to the LNG industry, where the supply chain's complexity necessitates robust risk management strategies.

Truong and Hara (2018) provide a detailed study on supply chain risk management in manufacturing- and service-oriented firms. The authors use Hierarchical Holographic Modeling (HHM) to compare the impact of various risks on the performance of manufacturing-oriented and service-oriented firms from a supply chain perspective. The study is based on a case study from the Vietnamese construction sector. The authors highlight the relevance of the study to the LNG industry. The study provides strategic guidelines to create new competitive advantages for the LNG industry through the adoption of these technologies.

The case studies and methodologies discussed here highlight several key aspects of risk management in the LNG industry. First, the need for a quantitative and methodological approach to risk assessment and management is evident. This involves identifying potential risks, quantifying their impact, and developing strategies for mitigation.

Second, the importance of supply chain risk management cannot be overstated in the LNG industry. Effective management of supply chain risks requires a comprehensive understanding of the entire value chain, from LNG production to transportation and delivery.

Third, internal communication and coordination are vital for effective risk management. This includes ensuring that all stakeholders, from frontline workers to top management, are aware of the risks and are actively involved in the risk management process.

Finally, the case studies suggest that adapting risk management strategies from other industries can be beneficial. The LNG industry can learn from the experiences and best practices of other sectors, such as retail and manufacturing, to enhance its risk management practices.

The efficacy of risk management strategies in the LNG industry is contingent upon a systematic, quantitative and collaborative approach. By learning from case studies and adapting best practices from other industries, the LNG industry can improve its risk management capabilities and ensure safer and more efficient operations.

3.3. Compliance with International HSE Standards: A Comparative Analysis

The adherence to international Health, Safety and Environmental (HSE) standards in the Liquefied Natural Gas (LNG) industry is pivotal for ensuring operational safety and environmental sustainability. This comparative analysis draws on various sectors to understand the application and compliance with these standards in the LNG industry.

Li et al. (2011) conducted a comparative study on the typical regulatory mechanisms for improving global mine safety and health. The study focuses on the insightful comparison of international mine safety and health standardization and regulation systems. The authors propose approaches to develop flexible, transparent and adaptable standards that respond to technological advancements and market changes. The study highlights the positive role of the current US safety framework, which results in a mutually supportive triangle consisting in law enforcement, technology and education/training. South Africa’s mine safety regulatory framework is based on a tripartite framework, state, employer

and employee. A new safety policy approach through multi-stakeholders has been proposed in China to continually improve their mine safety and health performance.

Chudnova, Potsulin and Shilov (2019) discuss the harmonization of Russian standards with international requirements, offering a pertinent example for the LNG industry. This study underscores the importance of aligning national standards with international norms, a critical aspect for the globally operating LNG industry. Harmonization ensures that products and operations meet international safety and quality benchmarks, facilitating global trade and cooperation.

Board (2015) provides safety guidelines for the construction and classification of nucleonic gauges and well logging applications. The document specifies regulatory requirements as well as methodologies for compliance by end users and suppliers of nucleonic gauges and well-logging sources. The well-logging devices incorporate relatively high activity neutron sources in addition to gamma sources, while the nucleonic gauging devices mostly incorporate low activity sources. The safety guidelines are significant for the LNG industry, and it is essential to comply with both national and international safety standards. The guidelines ensure that the devices are handled safely, from manufacture/supply, procurement, receipt from the supplier, installation, operation and decommissioning and disposal of the disused sources

Navigating the complex landscape of international and national HSE standards is a major challenge for the LNG industry. Compliance is essential not only for regulatory adherence but also for maintaining industry reputation and stakeholder trust. The industry must continuously update its practices to meet evolving standards and invest in ongoing improvements.

Comparative analysis reveals that while there are commonalities in HSE standards across different industries and regions, the LNG sector has specific requirements. These include standards related to the handling and storage of liquefied natural gas, emissions control and the safety of LNG transportation.

Technological advancements play a crucial role in achieving compliance with HSE standards. Advanced technologies enable more efficient monitoring, reporting and management of HSE-related data, facilitating compliance with complex regulatory requirements.

Employee training and development are key to ensuring compliance with HSE standards. A well-trained workforce is better equipped to understand and adhere to these standards, thereby enhancing the overall safety and environmental performance of the industry.

Compliance with international HSE standards in the LNG industry requires a multifaceted approach that includes understanding the global regulatory landscape, aligning national standards with international norms, leveraging technology and investing in human capital. By meeting these standards, the LNG industry can ensure safe, efficient and sustainable operations.

3.4. Technological Innovations and Their Impact on HSE

The integration of technological innovations in the Liquefied Natural Gas (LNG) industry has significantly influenced Health, Safety and Environmental (HSE) practices. These innovations are pivotal in transitioning towards a green economy, enhancing safety measures and improving operational efficiency.

Gonçalves (2014) explores the impact of shale gas on global LNG markets, highlighting the role of technological advancements in reshaping LNG trade, pricing and environmental considerations. The emergence of shale gas as a significant energy source has led to a paradigm shift in the LNG industry, necessitating the adoption of new technologies and practices to manage the associated HSE challenges effectively.

Almudhawi (2018) discusses the role of innovation in crisis management at ADNOC LNG, emphasizing the importance of adopting novel solutions in response to operational challenges. This approach is particularly relevant in the LNG industry, where handling emergencies requires a combination of technical expertise and situational awareness. The integration of innovative technologies and processes is crucial for enhancing safety and operational efficiency.

Bezerra de Melo and Eid (2018) introduce the concept of smart communicative cement for zonal isolation monitoring in the oil and gas industry, including LNG operations. This technology represents a significant advancement in well integrity management, offering real-time monitoring and improved safety measures. The application of such technologies in the LNG industry can enhance the safety and environmental sustainability of operations.

The LNG industry requires a high level of technical skill and knowledge. Training programs, therefore, must not only focus on technical aspects but also on developing soft skills such as communication, teamwork and decision-making. These skills are essential for ensuring safety and efficiency in complex operational environments.

Human factors also play a significant role in incident and accident prevention. Understanding human behavior, stress factors and decision-making processes can help in identifying potential risks and implementing effective safety measures.

The integration of technology in training and operations can enhance the understanding and management of human factors. Tools like VR and AI can simulate real-life scenarios, providing a safe environment for training and testing human responses to various situations.

Employee engagement and involvement are critical in developing a safety culture within the LNG industry. Encouraging participation in safety programs and decision-making processes ensures that safety becomes a shared responsibility, enhancing overall HSE performance.

Human factors are integral to the HSE practices of the LNG industry. Managing these factors through effective training, employee engagement and the integration of technology can significantly improve safety and operational efficiency. As the industry continues to evolve, the focus on human factors will remain a key component in achieving excellence in HSE practices.

3.5. Environmental Impact Assessment: Case Studies in LNG Operations

Environmental Impact Assessments (EIAs) play a crucial role in the Liquefied Natural Gas (LNG) industry, ensuring that the environmental implications of LNG operations are thoroughly evaluated and managed. This section explores case studies and methodologies employed in EIAs within the LNG industry, drawing insights from various sectors.

Prakash and Kolluru (2014) discuss the implementation of an integrated modelling approach for assessing environmental impacts in LNG operations. Their approach utilizes a 3-D comprehensive modelling framework, enabling a holistic assessment of the environmental impacts of operational and accidental releases in offshore LNG developments. This method allows for a cumulative assessment of environmental impacts, ensuring that all potential environmental risks are accounted for and managed effectively.

Dilay, Diduck and Patel (2020) provide a case study on environmental justice in India, focusing on the procedural aspects of EIAs in an industrial development project. Their study highlights the importance of public participation in the EIA process and the effectiveness of the court system in resolving disputes arising from EIAs. This case study underscores the need for inclusive and transparent EIAs in the LNG industry, ensuring that the concerns of potentially affected communities are adequately addressed.

Sarupria, Manjare and Girap (2019) present a comprehensive case study on EIA in a mining area in Goa, India, using a new approach that integrates the Rapid Impact Assessment Matrix (RIAM) with the Analytical Hierarchy Process (AHP). This approach overcomes limitations in existing EIA techniques, providing more precise and practical results for environmental impact assessment. The methodology is relevant to the LNG industry, where accurate and comprehensive EIAs are essential for sustainable operations.

The case studies highlight several key aspects of EIAs in the LNG industry. First, the need for a comprehensive and integrated approach to environmental impact assessment is evident. This involves not only identifying potential environmental impacts but also quantifying their severity and developing strategies for mitigation.

Second, the importance of public participation and community engagement in the EIA process cannot be overstated. Effective EIAs require all stakeholders' involvement, ensuring that local communities' concerns and knowledge are incorporated into the decision-making process.

Third, the role of technology in enhancing EIAs is increasingly significant. Advanced technologies enable more efficient data collection and analysis, facilitating a more thorough and accurate assessment of environmental impacts.

Finally, the case studies suggest that adapting EIA methodologies from other industries can be beneficial. The LNG industry can learn from other sectors' experiences and best practices, such as mining, to enhance its EIA practices.

Environmental Impact Assessments in the LNG industry require a systematic, comprehensive, and participatory approach. By learning from case studies and adapting best practices from other industries, the LNG industry can improve its EIA capabilities, ensuring environmentally sustainable operations.

3.6. Best Practices in HSE from Leading LNG Producers

The Liquefied Natural Gas (LNG) industry, with its complex operations and significant safety risks, necessitates the adoption of best practices in Health, Safety and Environmental (HSE) management. Leading LNG producers have developed and implemented various strategies and practices to ensure the highest standards of safety and environmental protection.

Peterson et al. (2019) discuss the safety aspects associated with LNG, including the unique hazards such as stratification, rollover and rapid phase transition. They emphasize the importance of adhering to existing codes and standards and provide a list of best practices for managing these risks. This approach is crucial for the LNG industry, where understanding and mitigating unique hazards are essential for safe operations.

Parfomak and Flynn (2004) provide a comprehensive study on the siting, safety, and regulation of liquefied natural gas (LNG) import terminals. The authors discuss consensus standards, best practices, and regulatory requirements related to process safety management (PSM) for LNG facilities. The study supports the need for continuous improvement and adaptation of PSM practices in response to evolving industry standards and technologies. The authors highlight the significance of LNG import terminals as a pivotal component in the global energy landscape. The study provides strategic guidelines to create new competitive advantages for the LNG industry through the adoption of these technologies.

Mantik (2018) addresses the application of High Resistance Grounding (HRG) in an Indonesian LNG plant, showcasing a best practice in electrical safety management. The use of HRG in low and medium voltage levels significantly enhances plant reliability and availability, reducing downtime due to short circuits. This case study demonstrates the importance of innovative electrical safety solutions in the LNG industry.

The adoption of best practices in the LNG industry involves several key aspects. First, a thorough understanding of the unique hazards associated with LNG operations is essential. This includes knowledge of the properties of LNG, potential risks during storage and transportation and the appropriate safety measures to mitigate these risks.

Second, compliance with international and national standards and regulations is crucial. LNG producers must stay abreast of the latest developments in safety and environmental regulations and ensure their operations meet these standards.

Third, technological innovation plays a significant role in enhancing HSE outcomes. The integration of advanced technologies in safety management systems, monitoring, and emergency response can significantly improve safety performance.

Fourth, employee training and development are critical components of HSE best practices. A well-trained workforce is better equipped to identify and respond to safety risks, thereby enhancing the overall safety culture within the organization.

Fifth, continuous improvement and adaptation are essential. The LNG industry is dynamic, with evolving technologies and regulatory landscapes. LNG producers must be proactive in updating their HSE practices to reflect these changes.

Sixth, stakeholder engagement and community involvement are important for ensuring comprehensive HSE management. This includes engaging with local communities, regulatory bodies, and industry partners to share knowledge and best practices.

Seventh, environmental sustainability should be a key consideration in HSE practices. LNG producers must strive to minimize their environmental footprint through efficient operations, emission control, and responsible resource management.

Leading LNG producers demonstrate a commitment to HSE excellence through the adoption of best practices in safety, environmental protection and regulatory compliance. By continuously improving and adapting these practices, the LNG industry can ensure safe, efficient, and sustainable operations.

4. Discussion of the Results

4.1. Interpreting the Efficacy of Current Risk Management Practices

The efficacy of current risk management practices in the Liquefied Natural Gas (LNG) industry is a critical area of study, given the high stakes involved in LNG operations. The industry faces unique challenges due to the volatile nature of the product, the complexity of the supply chain and the stringent regulatory environment. This section explores various methodologies and analyses employed in the LNG industry to manage risks effectively.

Iannaccone (2021) discusses the safety and sustainability assessment of marine LNG technologies, focusing on small-scale applications. The study provides an in-depth evaluation of the safety of existing technologies for LNG bunkering and onboard fuel gas supply systems. This research is crucial for the LNG industry as it provides key information about credible accident scenarios and their expected consequences, thereby aiding in the development of effective risk management strategies.

Fan, Enshaei and Jayasinghe (2021) conducted a comprehensive literature review on the safety philosophy and risk analysis methodology for Liquefied Natural Gas (LNG) bunkering simultaneous operations (SIMOPs). This research is pivotal in understanding the intersection of safety philosophical factors and risk management within the maritime industry, particularly in the context of LNG bunkering. The findings from this study contribute significantly to the body of knowledge in the maritime sector, emphasizing the importance of integrating safety philosophy into risk management practices to enhance operational safety in LNG bunkering. The study investigates the relationship between safety philosophical factors and risk management in the maritime industry, which is closely related to the LNG sector. The findings from this research are crucial for improving safety standards and practices in LNG bunkering operations, a key area in the maritime industry.

Talabi and Fishchbeck (2014) provide an empirical evaluation of risk management practices in nuclear power plant Engineering, Procurement and Construction (EPC) projects. While focusing on the nuclear industry, the insights from this study are applicable to the LNG industry, particularly in understanding the limitations of current risk management practices and the need for accurate risk assessments.

The case studies and methodologies discussed here highlight several key aspects of risk management in the LNG industry. First, the need for a comprehensive and methodological approach to risk assessment and management is evident. This involves not only identifying potential risks but also quantifying their impact and developing strategies for mitigation.

Second, the importance of safety philosophy in risk management is highlighted. Integrating safety philosophical factors into risk management practices can significantly enhance the effectiveness of these practices in the LNG industry.

Third, the role of empirical evaluations in advancing risk management practices is crucial. Studies like those on nuclear power plant EPC projects provide valuable insights into the effectiveness of current risk management practices and areas for improvement.

Finally, the case studies suggest that adapting risk management strategies from other industries can be beneficial. The LNG industry can learn from the experiences and best practices of sectors such as maritime and nuclear to enhance its risk management practices.

The efficacy of risk management strategies in the LNG industry is contingent upon a systematic, comprehensive and philosophical approach. By learning from case studies and adapting best practices from other industries, the LNG industry can improve its risk management capabilities and ensure safer and more efficient operations.

5. 4.2. Regulatory Compliance: Challenges and Achievements

Like many others, the Liquefied Natural Gas (LNG) industry faces significant regulatory compliance challenges, which are crucial for ensuring safety, environmental protection and operational efficiency. This section explores the challenges and achievements in regulatory compliance within the LNG industry, drawing insights from related sectors.

Bui and Perera (2019) discuss the compliance challenges in emissions control regulations to reduce air pollution from shipping, a sector closely related to the LNG industry. The study highlights the difficulties in complying with regulations

aimed at reducing sulfur oxides (SOx) emissions. These challenges include selecting compliant fuels, integrating emission abatement technologies, and adopting alternative fuels like LNG. The insights from this study are relevant to the LNG industry, which also grapples with stringent environmental regulations and the need for technological adaptation.

Abdullah, Sadiq and Indulska (2010) examine the challenges in managing regulatory compliance from the perspective of the Australian compliance industry. The study reveals core challenges such as the speed of regulatory changes, organizational culture, risk management, resource scarcity and the perception of compliance as a non-value-adding activity. These challenges resonate with the LNG industry, where rapid regulatory changes and the need for a compliance-oriented culture are critical for successful operations.

Kheni and Afatsawu (2022) investigate the challenges faced by regulatory authorities in implementing health and safety compliance in the Ghana construction industry. The findings indicate issues such as the lack of a comprehensive national policy, ineffective supervision and the inability to prosecute companies violating standards. These challenges are similar to those faced in the LNG industry, where ensuring compliance with health and safety standards is paramount for safe operations.

The LNG industry's regulatory compliance challenges are multifaceted. First, the rapid pace of regulatory changes requires the industry to be agile and responsive. Keeping up with evolving standards and adapting operations accordingly is a continuous challenge.

Second, achieving a compliance-oriented organizational culture is crucial. This involves fostering an environment where compliance is viewed as integral to business operations rather than a burdensome requirement.

Third, effective risk management is key to regulatory compliance. Identifying, assessing and mitigating risks associated with non-compliance are essential for maintaining operational integrity and reputation.

Fourth, resource allocation for compliance activities is a significant challenge. Ensuring adequate resources, both financial and human, are available for compliance-related tasks is essential for meeting regulatory requirements.

Fifth, the perception of compliance as a value-adding activity needs to be reinforced. Moving beyond the view of compliance as a mere legal requirement to understanding its role in enhancing safety, environmental stewardship and operational efficiency is crucial.

Sixth, technological adaptation plays a significant role in achieving compliance. Leveraging technology for monitoring, reporting and managing compliance-related data can enhance the efficiency and effectiveness of compliance efforts.

Seventh, collaboration with regulatory authorities is important. Engaging with regulators, understanding their perspectives and working together can lead to more practical and effective compliance strategies.

Regulatory compliance in the LNG industry involves navigating a complex landscape of challenges. By addressing these challenges through strategic planning, technological adaptation and fostering a compliance-oriented culture, the industry can achieve significant achievements in regulatory compliance, ensuring safe, sustainable and efficient operations.

4.3. Environmental Sustainability in the LNG Sector: Progress and Pitfalls

The environmental sustainability of the Liquefied Natural Gas (LNG) sector is a topic of increasing importance, given the global push towards cleaner energy sources. This section explores the progress and pitfalls in achieving environmental sustainability in the LNG industry, drawing insights from various studies.

Jeong et al. (2020) discuss the development of a regulatory framework to foster sustainable LNG bunkering operations. The authors highlight the challenges associated with methane emissions during the production and use of LNG and the need for regulatory frameworks to minimize environmental impacts. The study provides strategic guidelines to create new competitive advantages for the LNG industry through the adoption of these technologies.

Sandri, Hussein and Alshyab (2020) examine the sustainability of the energy sector in Jordan, providing insights into the broader context of energy security and environmental sustainability. Their study underscores the importance of

diversifying the energy mix and investing in renewable energy sources. The relevance to the LNG sector lies in the need for a balanced approach that considers environmental, economic, social and political sustainability.

Butarbutar and Gurning (2022) review the use of LNG as marine fuel within the Indonesian shipping sector. The study highlights the environmental benefits of LNG, including significant reductions in sulfur emissions and carbon output. However, it also points out the slow progress in alternative energy development, emphasizing the need for the LNG industry to continuously innovate and improve its environmental performance.

The LNG sector has made considerable progress in environmental sustainability, primarily through the adoption of LNG as a cleaner alternative to traditional fossil fuels. The reduction in greenhouse gas emissions and the potential for lower carbon footprints are significant achievements.

However, the industry faces several pitfalls. Methane emissions during LNG production and use are a major concern, given methane's higher global warming potential compared to carbon dioxide. Addressing these emissions is crucial for the environmental credibility of LNG.

Regulatory frameworks play a critical role in promoting environmental sustainability in the LNG sector. The development and implementation of regulations that address emissions and other environmental impacts are essential for guiding the industry towards more sustainable practices.

The integration of LNG into the broader energy mix presents both opportunities and challenges. While LNG can serve as a bridge fuel in the transition to renewable energy sources, there is a risk of over-reliance on LNG, which could hinder the development of cleaner energy technologies.

Investment in research and development is key to overcoming the environmental challenges associated with LNG. Innovations in technology and processes can lead to more efficient and environmentally friendly LNG operations.

Stakeholder engagement and public perception are important factors in the sustainability journey of the LNG sector. Gaining public trust and support requires transparent communication about the environmental impacts and benefits of LNG.

The LNG industry must balance economic growth with environmental responsibility. While LNG offers economic advantages, its environmental impacts must be carefully managed to ensure long-term sustainability.

The environmental sustainability of the LNG sector has seen significant progress, but it is not without its challenges. Addressing these challenges requires a multifaceted approach involving regulatory frameworks, technological innovation, stakeholder engagement and a commitment to continuous improvement. By navigating these complexities, the LNG industry can contribute to a more sustainable energy future.

6. Conclusion

The comprehensive review of Health, Safety and Environmental (HSE) practices in the Liquefied Natural Gas (LNG) industry has successfully met its aim and objectives, providing a deep and nuanced understanding of the sector's current state. This study meticulously evaluated the challenges, risk management strategies, regulatory compliance, technological advancements and environmental sustainability within the LNG industry, aligning closely with the outlined objectives. Key findings from the study reveal a landscape marked by complex challenges and dynamic advancements.

The study identified significant HSE challenges in the LNG industry, including operational risks, environmental impacts and safety concerns, necessitating a balance between operational efficiency and stringent safety measures. In terms of risk management strategies, the efficacy of existing practices was critically analyzed, highlighting the need for comprehensive, methodological approaches and the integration of safety philosophy into risk management practices. The study also shed light on the multifaceted nature of regulatory compliance within the industry, emphasizing the rapid pace of regulatory changes, the importance of a compliance-oriented organizational cultures and the critical role of technological adaptation in achieving compliance.

Technological innovations were found to significantly impact HSE practices, enhancing safety management systems and environmental performance. The study underscored the environmental benefits of LNG as a cleaner fuel alternative,

while also pointing out the challenges associated with methane emissions and the necessity for robust regulatory frameworks to mitigate environmental impacts.

In conclusion, this study provides valuable insights and recommendations for industry stakeholders, policymakers and researchers. It advocates for continuous improvement in HSE practices, leveraging technological innovations, fostering a compliance-oriented culture and adopting a multifaceted approach to manage the complex HSE challenges in the LNG sector. The findings underscore the importance of balancing economic growth with environmental responsibility and safety, ensuring the LNG industry's sustainable development. This study contributes significantly to the body of knowledge on HSE practices in the LNG industry and serves as a foundation for future research and policy development in this critical energy sector.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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