



Automation and worker safety: Balancing risks and benefits in oil, gas, and renewable energy industries

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Abstract

The integration of automation in the oil, gas, and renewable energy industries has revolutionized operational efficiency and worker safety. This paper examines the dual role of automation in mitigating workplace hazards while addressing the associated risks and challenges. The objectives include evaluating how automated systems reduce human exposure to high-risk tasks, identifying potential risks introduced by automation, and proposing strategies to balance safety with technological advancement.

Key findings highlight that automation significantly reduces accidents in high-hazard environments, such as offshore rigs and wind turbine maintenance, by replacing manual tasks with remote-controlled or autonomous systems. However, the increased reliance on automated technologies presents new challenges, including cybersecurity vulnerabilities, system failures, and the need for specialized training. Furthermore, the shift toward renewable energy introduces unique safety considerations, such as managing risks in battery storage and photovoltaic system maintenance.

The paper concludes that while automation offers substantial benefits in enhancing worker safety, a holistic approach is essential to address its challenges. Strategies such as robust risk assessments, adaptive safety protocols, and comprehensive worker training programs are crucial to mitigate the unintended consequences of automation. By fostering collaboration between industry stakeholders and regulatory bodies, the oil, gas, and renewable energy sectors can achieve a sustainable balance between leveraging automation and safeguarding worker well-being. This research underscores the need for ongoing innovation and vigilance to ensure that automation remains a tool for enhancing, rather than compromising, workplace safety.

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1. Introduction

1.1. Importance of Automation in Energy Industries: Introduction to the increasing role of automation in improving operational efficiency and safety in oil, gas, and renewable energy sectors.

The increasing integration of automation in the energy industries, particularly in oil, gas, and renewable energy sectors, marks a pivotal shift toward enhancing operational efficiency and ensuring worker safety. Automation, defined as the application of

technology to perform tasks with minimal human intervention, is transforming these industries by optimizing processes, reducing costs, and mitigating workplace hazards. The complexity and hazardous nature of energy production and distribution have necessitated technological advancements, making automation not only a strategic asset but also a safety imperative.

In oil and gas, automation technologies such as robotic drilling systems, autonomous underwater vehicles, and digital twins have significantly reduced human exposure to high-risk environments, including offshore rigs and deep-sea explorations. These advancements enable precise operations in extreme conditions, thereby reducing accidents caused by human error. Similarly, the renewable energy sector has embraced automation to enhance efficiency in solar and wind energy production, with automated monitoring systems improving the reliability and safety of photovoltaic plants and wind turbines.

Despite its transformative potential, the implementation of automation introduces challenges that require careful consideration. One significant issue is the displacement of skilled labor, leading to workforce disruptions. Furthermore, the reliance on complex automated systems increases vulnerabilities to cybersecurity threats and system failures, which can pose risks to both operations and worker safety. Addressing these challenges necessitates a balanced approach that integrates robust safety protocols, continuous worker training, and advanced cybersecurity measures to ensure that automation fulfills its potential as a catalyst for progress.

The role of automation in renewable energy is particularly critical in achieving global sustainability goals. The integration of artificial intelligence and machine learning in energy management systems allows for real-time data analysis, optimizing energy production and consumption patterns. For instance, smart grids leverage artificial intelligence to enhance energy distribution efficiency, reducing wastage and ensuring uninterrupted supply. Such innovations underscore the importance of automation in driving the transition to cleaner energy sources while maintaining high safety standards for workers and infrastructure.

The interrelation between automation and safety in these industries is further emphasized by regulatory frameworks and industry standards that promote safe automation practices. Organizations are increasingly adopting international standards for occupational health and safety management to guide the integration of automation technologies. These frameworks ensure that automation not only improves operational efficiency but also aligns with ethical and safety considerations, protecting both human and environmental well-being.

Automation represents a cornerstone of innovation in the energy industries, offering immense benefits in operational efficiency and safety. However, its successful implementation requires a nuanced approach that addresses associated risks and challenges. By fostering collaboration between industry stakeholders, regulatory bodies, and technological innovators, the oil, gas, and renewable energy sectors can harness the full potential of automation to drive progress while safeguarding the workforce. This paper underscores the critical need for strategic planning and policy-making to ensure that automation remains a tool for sustainable development and safety enhancement in the

energy industries.

1.2. Objectives of the Review

The primary objective of this review is to systematically evaluate the increasing application of automation in enhancing worker safety across oil, gas, and renewable energy industries. This entails assessing the effectiveness of automation technologies in mitigating occupational hazards, improving operational efficiency, and supporting the transition to sustainable energy production. Furthermore, the review aims to identify the risks and challenges associated with automation, such as cybersecurity vulnerabilities, technological failures, and workforce displacement, while proposing strategies to address these concerns within the framework of industry best practices.

The review seeks to provide a comprehensive understanding of how automation minimizes exposure to high-risk tasks, thereby reducing the likelihood of workplace accidents. In industries like oil and gas, where operations often involve hazardous environments such as offshore platforms and drilling rigs, the deployment of robotic systems and remote-controlled machinery has been pivotal in safeguarding workers. Similarly, in renewable energy sectors, automated monitoring systems have enhanced the safety and reliability of solar and wind energy production processes, particularly during installation and maintenance activities.

An additional objective is to examine the alignment of automation with regulatory and safety standards, ensuring that technological advancements adhere to global occupational health protocols. The review highlights the role of international frameworks in fostering a culture of safety, particularly in high-risk sectors, while emphasizing the importance of regular assessments to address emerging threats posed by advanced technologies.

To achieve these objectives, the review adopts a multidisciplinary approach, incorporating insights from engineering, environmental science, and occupational health studies. By synthesizing findings from diverse fields, this study aims to provide actionable recommendations for policymakers, industry leaders, and safety professionals. This will ensure that automation is harnessed not only as a tool for operational efficiency but also as a cornerstone for advancing worker safety and well-being in energy industries.

The objectives of this review are aligned with the overarching goal of fostering innovation while maintaining rigorous safety standards. By exploring the interplay between automation and worker safety, the review aims to bridge the gap between technological advancement and practical implementation in real-world scenarios. This alignment is critical in ensuring that automation continues to serve as a driving force for progress in the energy sector while safeguarding human lives and promoting sustainable practices.

1.3. Clarification of the review's aims and scope, focusing on evaluating the safety benefits of automation while addressing potential risks and their mitigation

Automation has become an integral part of modern industries and systems, promising unparalleled benefits in efficiency and safety. However, its adoption raises significant questions about the balance between its safety advantages and the potential risks it introduces. This review aims to examine the safety benefits of automation, identify the associated risks, and explore strategies for their mitigation. By evaluating

recent advancements and practical implementations, the discussion underscores how automation can be both a boon and a challenge in safety-critical domains.

The promise of automation lies in its ability to enhance operational safety by minimizing human error, performing hazardous tasks, and maintaining system stability under challenging conditions. For instance, automation systems, such as adaptive automation frameworks, have been designed to assist human operators in critical scenarios, thus reducing the likelihood of accidents arising from human oversight or fatigue (Inagaki & Itoh, 2007) ^[13]. Similarly, frameworks like SafetyOps have emerged, integrating advanced practices to ensure the safety lifecycle of autonomous systems, thereby mitigating risks through real-time interventions (Siddique, 2020) ^[32].

Despite these advantages, automation is not devoid of challenges. One critical issue is the phenomenon of risk compensation, where individuals may engage in riskier behavior due to over-reliance on automation, potentially offsetting its intended safety benefits (Itoh, Sakami & Tanaka, 2000) ^[15]. Additionally, the integration of safety mechanisms such as Safety Integrity Levels (SIL) has shown to reduce fatal risks in automated processes, yet these systems must contend with the unpredictability of human-automation interactions and the potential for systemic failures.

The implementation of automation systems often requires a delicate balance between maximizing reliability and minimizing risks. For example, industrial safety standards such as IEC 61508 provide guidelines for enhancing the safety of programmable control systems, which are essential for maintaining high safety integrity levels in complex industrial setups (Krosigk, 2000) ^[36]. However, the challenge lies in unifying these standards across industries to ensure consistent safety benchmarks, as observed in comparative studies of Performance Level (PL) and SIL (Ciucias, Nowakowski & Pietruszczak, 2019) ^[7].

Moreover, as automation systems become increasingly sophisticated, new frameworks are being developed to dynamically adapt to evolving operational environments. The integrati learning and real-time monitoring systems has proven effective in managing safety risks, more proactive approach to addressing potential failures (McDermid, Jia & Habli, 2019) ^[25]. However, these advancements also bring about concerns related to cybersecurity and the vulnerability of automated systems to external threats, underscoring the need for robust intrusion detection mechanisms (Schuster & Paul, 2012) ^[30].

While automation presents remarkable opportunities for enhancing safety in various domains, its adoption must be accompanied by a thorough understanding of its limitations and risks. By leveraging advanced technologies, adhering to stringent safety standards, and fostering human-machine synergy, the potential risks associated with automation can be mitigated. This review seeks to provide a nuanced perspective on these dynamics, contributing to the broader discourse on the safe and effective implementation of automation in critical systems.

1.4. Current Challenges in Worker Safety and Automation: Discussion of challenges such as ensuring workforce adaptability, managing new risks from automation, and balancing human and machine integration in hazardous environments

The integration of automation into workplace safety presents

a paradox. On the one hand, it has revolutionized industries by enhancing efficiency and mitigating traditional risks. On the other hand, it introduces new challenges that demand strategic management to ensure workforce adaptability, risk control, and seamless integration between human and machine in hazardous environments. This review explores these challenges, emphasizing the pressing need for adaptive safety measures and collaborative systems.

Automation underpins the promise of reducing worker exposure to dangerous tasks by streamlining operations. However, this shift brings with it psychosocial stresses due to changing roles and responsibilities, particularly in Industry 4.0. The evolving nature of work necessitates continuous training and reassessment of occupational safety frameworks to equip workers with the skills needed to navigate automated systems effectively.

The challenge of managing risks introduced by automation is further compounded by the need for robust safety mechanisms. The reliance on automated machine guarding systems underscores the importance of implementing protective measures from the onset of automation processes. Similarly, advancements in tools like Safety Integrity Levels (SIL) and real-time monitoring systems have been pivotal in mitigating risks but require a high degree of precision and constant oversight to maintain efficacy.

Balancing human and machine integration in hazardous settings involves addressing ergonomic and cognitive risks. Risks associated with autonomous maintenance, where untrained operators take on tasks traditionally performed by skilled personnel, expose them to potential hazards. This shift necessitates not only technical training but also the development of comprehensive risk identification and mitigation strategies.

Furthermore, automation does not eliminate all risks; it transforms them. Workers face indirect risks associated with new technologies, such as data-driven safety solutions. Integrating safety management systems that evolve with the lifecycle of technical devices in high-risk industries is critical. Similarly, IoT-based solutions, like those implemented in safety helmets for construction sites, aim to proactively alert workers to potential dangers but rely heavily on the accuracy and timeliness of data.

Worker adaptability remains a critical concern. Robotic systems reduce traditional risks but also introduce novel threats, requiring workers to adapt rapidly to unfamiliar technologies. This adaptation often hinges on comprehensive safety training programs and a supportive organizational culture that prioritizes safety. Hierarchical workplace structures can impede active worker participation in safety programs, highlighting the importance of collaborative approaches in accident prevention.

The intersection of worker safety and automation presents a complex landscape of opportunities and challenges. While automation promises to revolutionize safety protocols, it necessitates an equally robust framework for risk management and worker adaptation. By fostering collaboration between humans and machines and investing in advanced safety technologies, organizations can navigate this transition effectively, ensuring a safer and more adaptable workforce.

2. Literature Review

2.1. Overview of Automation Technologies in Energy Industries: Exploration of automation technologies

commonly used in oil, gas, and renewable energy industries, such as robotics, IoT systems, autonomous vehicles, and AI-powered monitoring systems.

The energy industry has witnessed a significant transformation with the advent of automation technologies that enhance efficiency, reduce environmental impact, and ensure operational safety. In the oil, gas, and renewable energy sectors, tools such as robotics, IoT systems, autonomous vehicles, and AI-powered monitoring systems play pivotal roles. This literature review provides an in-depth examination of these technologies, emphasizing their applications and contributions to advancing energy industries.

Robotic systems are increasingly used in hazardous environments to perform tasks that would otherwise pose significant risks to human workers. For example, robotics can be deployed for pipeline inspections, reducing the likelihood of accidents and ensuring continuous monitoring of system integrity. Their precision and ability to function in extreme conditions make them indispensable in offshore oil platforms and remote renewable energy facilities. The adoption of autonomous robotic technologies has not only improved safety but has also enhanced the efficiency of routine and emergency operations, a critical aspect in managing complex energy infrastructures (Panevnik, 2021).

The integration of IoT systems into the energy sector has revolutionized real-time monitoring and data analysis. These systems enable the seamless connection of equipment, sensors, and control units, fostering a comprehensive understanding of operational dynamics. In oil and gas production, IoT technologies facilitate predictive maintenance, minimizing downtime and optimizing resource utilization. Similarly, in renewable energy sectors like solar and wind power, IoT systems monitor energy generation and grid integration, ensuring efficiency and stability in energy distribution (Cimino et al., 2015; Kryukov, 2016)^[6, 20].

Autonomous vehicles are another critical innovation in energy industries. They are employed for material transport in oil fields and renewable energy installations, where terrain and environmental conditions pose logistical challenges. By reducing reliance on manual operations, these vehicles enhance safety and operational efficiency. Their application in offshore wind farms, for example, underscores their versatility in addressing the unique challenges of renewable energy generation (Sheludko et al., 2018)^[31].

AI-powered monitoring systems are at the forefront of automation technologies in the energy industry. These systems leverage machine learning algorithms to analyze vast datasets, predict failures, and optimize processes. In the oil and gas sector, AI facilitates reservoir management, drilling optimization, and environmental impact assessments. For renewable energy, AI algorithms optimize energy storage and distribution, balancing supply and demand while reducing waste. These systems exemplify the integration of advanced computational techniques to address the complexities of energy production and consumption (Smith, 2016)^[33].

Hybrid energy solutions exemplify the role of automation technologies in integrating traditional and renewable energy sources. The use of photovoltaic (PV) systems alongside diesel generators in oil fields highlights the industry's shift toward sustainable practices. Studies demonstrate that hybrid systems not only reduce operational costs but also significantly cut greenhouse gas emissions, showcasing their environmental and economic benefits (El-Yamany et al.,

2021)^[9].

In the renewable energy domain, automation technologies have enabled the deployment of advanced control systems for solar and wind energy farms. These systems ensure the optimal alignment of solar panels and wind turbines, maximizing energy capture. Additionally, AI-driven analytics support grid management by predicting energy demand and supply fluctuations, ensuring stability in power distribution networks (Smith, 2016; Kryukov, 2016)^[33, 20].

The adoption of these technologies in the energy industry underscores a commitment to innovation, efficiency, and sustainability. As the sector continues to evolve, the integration of robotics, IoT systems, autonomous vehicles, and AI-powered monitoring will likely expand, driving further advancements in energy production and management.

2.2. Benefits of Automation for Worker Safety: Analysis of how automation reduces safety risks, such as exposure to hazardous environments, repetitive stress injuries, and fatigue-related incidents.

Automation has emerged as a transformative force in improving workplace safety by significantly mitigating risks associated with hazardous environments, repetitive stress injuries, and fatigue-related incidents. This literature review explores these benefits, emphasizing how automation technologies enhance safety through innovation and efficiency.

Automation technologies, including robotics and autonomous systems, reduce the need for human presence in hazardous environments. For instance, robots can take over tasks such as operating in toxic or high-temperature areas, which traditionally posed severe health risks to workers. These systems not only improve safety but also enhance operational efficiency by performing tasks with greater precision and consistency (Kaylo et al., 2023)^[17]. Similarly, in roadside construction, automated traffic management and machinery have been shown to reduce road worker fatalities by over 30%, highlighting their efficacy in high-risk zones (Bergquist et al., 2013)^[2].

Another significant advantage of automation lies in mitigating repetitive stress injuries. Repetitive tasks often lead to musculoskeletal disorders, which are a major cause of workplace absenteeism. Automation addresses this by taking over such tasks, thereby reducing physical strain on workers. For example, automated manufacturing systems are designed to handle tasks like lifting, assembly, and material transport, creating safer work environments while also increasing productivity (Floyd, 2011)^[10]. Furthermore, immersive technologies, such as virtual reality (VR) simulators, enhance employee training by providing risk-free environments for practice, reducing errors and injuries caused by human factors (Simonov, 2020).

Fatigue-related incidents, a prevalent safety issue, are also effectively mitigated through automation. Fatigue can impair decision-making and reaction times, leading to accidents. Automated systems can operate continuously without performance degradation, significantly lowering the risk of incidents due to worker exhaustion. In manufacturing, for instance, automation ensures consistent production quality and reduces the physical and cognitive workload on employees, thereby minimizing burnout and improving morale (Sedore, 2023).

During the COVID-19 pandemic, automation played a crucial role in maintaining workplace safety by reducing

employee exposure to potential contagion. Automated systems, including digitized and soft automation configurations, minimized human interaction in manufacturing environments, demonstrating their adaptability in addressing emergent risks (Heredia et al., 2022) ^[11]. Moreover, smart technologies, such as the SAFE helmet, exemplify how integrated sensors and autonomous alerts can proactively enhance worker protection in industrial settings (Altamura et al., 2019) ^[1].

While the benefits of automation for safety are well-documented, it is essential to consider the challenges and limitations associated with its implementation. Automation can introduce new risks, such as over-reliance on systems or the potential for technical failures. Thus, a balanced approach that includes comprehensive safety assessments and human oversight is necessary to maximize the benefits of these technologies while mitigating potential drawbacks (Oglesby et al., 2014) ^[27].

Automation significantly enhances worker safety by reducing exposure to hazardous environments, preventing repetitive stress injuries, and addressing fatigue-related risks. Through advancements in robotics, immersive training technologies, and integrated safety systems, automation continues to reshape workplace safety. However, the integration of automation must be accompanied by robust risk management strategies to ensure its effectiveness and reliability in diverse industrial contexts.

2.3. Risks Associated with Automation in Energy Industries: Examination of risks, including over-reliance on technology, cybersecurity vulnerabilities, workforce displacement, and new safety hazards introduced by automated systems.

The integration of automation technologies in the energy industry has transformed operational efficiencies, safety, and sustainability. However, this evolution introduces critical risks that require careful examination, including over-reliance on technology, cybersecurity vulnerabilities, workforce displacement, and new safety hazards. This review explores these dimensions, highlighting their implications for energy industry stakeholders.

Over-reliance on technology represents a significant risk, as increased dependence on automated systems can lead to vulnerabilities when these systems fail or perform unpredictably. Automation, while minimizing human intervention, may lead to oversight errors or system failures. For example, the integration of inverter drives in industrial energy systems enhances efficiency but also introduces risks of control failures and interference in operations (Leonowicz & Lempart, 2012) ^[22]. These risks necessitate robust redundancy mechanisms and continuous system monitoring to maintain operational integrity.

Cybersecurity vulnerabilities are among the most pressing concerns in the automation of the energy sector. Automated systems in energy grids are particularly susceptible to cyber-attacks, such as False Data Injection (FDI) and Denial of Service (DoS) attacks, which can compromise grid reliability and cause widespread disruptions (Li et al., 2024). The adoption of Distributed Energy Resources (DER) introduces additional attack vectors due to the decentralized nature of these systems, further complicating risk management strategies (Kumar & Jayantilal, 2011) ^[21]. Addressing these threats requires the integration of advanced cybersecurity measures, as emphasized by Kosmowski et al. (2022) ^[18],

who propose a business continuity management framework to mitigate cyber risks effectively.

Workforce displacement poses another critical challenge associated with automation. The introduction of AI and robotics in the energy sector reduces the demand for certain roles, leading to economic and social implications for affected workers. This issue extends beyond the energy sector, as highlighted by Trunina et al. (2023) ^[34], who discuss the broader risks of job displacement due to AI technologies. Ethical frameworks and policies are crucial to managing this transition, ensuring that displaced workers are retrained for roles that complement automated processes.

In addition to these systemic risks, new safety hazards emerge with the deployment of automated systems. The complexity of automation can introduce unanticipated interactions between components, leading to accidents. Furthermore, automation often requires specialized knowledge for maintenance and troubleshooting, which can exacerbate operational risks if adequately trained personnel are unavailable. For instance, Kostyunina (2018) ^[19] highlights the importance of data mining technologies for analyzing and classifying cyber risks, underscoring the need for skilled professionals to address these challenges.

The rapid integration of automation in energy industries calls for a balanced approach that maximizes its benefits while addressing associated risks. Comprehensive risk assessment frameworks and robust cybersecurity protocols are essential to safeguarding against technological vulnerabilities. Additionally, workforce adaptability must be prioritized through training programs and policy interventions to mitigate the socioeconomic impacts of automation. By acknowledging and addressing these risks, the energy sector can navigate its automation journey effectively, ensuring sustainable growth and resilience.

2.4. Role of Human-Machine Collaboration: Discussion of the importance of balancing human oversight with automation to maintain safety and adaptability in energy operations.

The increasing reliance on automation within the energy industry has highlighted the crucial need for effective human-machine collaboration to maintain safety and adaptability. This literature review explores the balance between automation and human oversight, emphasizing its importance in energy operations to ensure operational efficiency and safety.

Human operators remain indispensable in the supervision of complex energy systems, particularly in tasks requiring adaptability and critical decision-making. As noted by Meshakti (2007) ^[26], the interplay between human, organizational, and technological subsystems is vital for preventing catastrophic failures and maintaining reliability in energy operations (Meshakti, 2007) ^[26]. The evolving relationship between humans and machines necessitates novel safety concepts that integrate advanced technologies such as IoT, AI, and ICT, promoting harmonious interactions within industrial environments (Kanamaru & Ogihara, 2019) ^[16]. In high-risk tasks, such as high-voltage electrical operations, collaborative robotic systems have shown significant promise. These systems allow human operators to manage operations remotely, minimizing direct exposure to hazards while leveraging the precision and efficiency of automation. Wang et al. (2023) ^[37] demonstrated that dual-arm collaborative robots equipped with human-computer

interaction interfaces not only enhance safety but also reduce operational risks in energy environments (Wang et al., 2023)^[37]. Similarly, the concept of “Symbiotic Safety,” as explored by Ishigooka et al. (2022)^[14], involves the dynamic adjustment of action plans and safety rules to optimize collaboration between humans and machines, ensuring both safety and efficiency (Ishigooka et al., 2022)^[14].

Advanced human-machine interfaces are also transforming the landscape of occupational safety. Real-time monitoring systems that measure human cognitive states, such as EEG-based systems, enable machines to adapt their behavior based on the operator’s mental workload, thereby enhancing safety in energy operations. These systems exemplify the synergy between human adaptability and machine precision, a cornerstone of effective collaboration.

The integration of automation has also necessitated innovative safety protocols, particularly in collaborative environments. Califano et al. (2022)^[5] introduced a task-based safety protocol that uses energy constraints to minimize collision risks in human-robot interactions, demonstrating its efficacy in maintaining operational safety in shared workspaces (Califano et al., 2022)^[5]. Similarly, Pini and Leali (2019)^[29] highlighted the importance of computer-aided assessments to design safety countermeasures in industrial applications, ensuring compliance with rigorous safety standards (Pini & Leali, 2019)^[29].

In collaborative manufacturing scenarios within Industry 4.0, safety assurance has become a critical component of human-machine collaboration. By integrating real-time safety monitoring and adaptive control measures, systems can address potential hazards proactively, sustaining safety across all operational components (Bi et al., 2021). The role of augmented reality (AR) technologies, such as ABB Ability Augmented Field Procedures, further underscores the importance of enhancing information exchange between human operators and automated systems in ensuring workplace safety.

Human-machine collaboration is indispensable in balancing the benefits of automation with the necessity of human oversight in energy operations. Through advanced interfaces, adaptive safety protocols, and integrative technologies, this collaboration fosters a safer and more adaptable operational environment. The energy sector must continue to invest in these synergistic approaches to harness the full potential of automation while safeguarding human involvement.

2.5. Case Studies of Automation Impact on Worker Safety: Review of specific case studies showcasing the benefits and challenges of automation in improving worker safety in oil, gas, and renewable energy operations.

Automation has significantly impacted worker safety in energy industries, including oil, gas, and renewable energy operations. Through various case studies, the benefits and challenges of implementing automation in these sectors are evident, highlighting real-world applications and their implications for safety and operational efficiency.

One notable case involves implementing formal modeling to improve safety and security in automated manufacturing systems. This approach analyzed risk identification and mitigation in these systems, providing valuable insights into worker safety within energy industries. It underscored the importance of using formal methods to address the inherent risks associated with automation.

In the oil and gas sector, automation has played a pivotal role in managing safety for technical devices such as tanks, boilers, and pipelines. The critical role of automation in maintaining safety throughout the equipment's service life has been demonstrated, illustrating its application in hazardous environments. Automation has contributed to reducing workplace risks by enhancing monitoring and control systems.

The adoption of augmented reality (AR) technologies has further enhanced occupational safety systems in energy operations. AR's application in power plant settings has improved risk assessment and employee protection. This technology has demonstrated potential by providing workers with real-time information, enhancing situational awareness, and mitigating safety risks.

Automation has also been instrumental in designing advanced safety management programs for energy sector employees. Comprehensive safety management approaches have addressed typical safety management challenges and significantly improved worker safety by integrating risk assessment and preventive measures.

In renewable energy, ergonomic assessments have been integrated into automation strategies to enhance worker safety and health. Evaluations of ergonomic factors have provided biomechanical recommendations that reduced worker complaints and optimized workplace conditions, ensuring safety in automated energy operations.

Despite these advancements, automation in energy industries presents challenges that require careful consideration. While advanced technologies improve safety in manufacturing jobs, they also introduce new risks for operators. The necessity of safety engineering in designing automated systems has been emphasized to safeguard workers effectively.

These case studies illustrate the transformative role of automation in improving worker safety across oil, gas, and renewable energy sectors. By integrating advanced technologies such as AR, formal modeling, and ergonomic assessments, automation has reduced workplace hazards and enhanced operational efficiency. However, addressing the challenges associated with automation, such as new safety risks and the need for rigorous safety engineering, remains critical to ensuring its long-term success in energy operations.

3. Benefits and Challenges

3.1. Benefits of Automation in Enhancing Safety:

Discussion of benefits such as reduced human exposure to hazardous tasks, enhanced predictive maintenance, and improved incident response times.

Automation plays a pivotal role in enhancing worker safety within the energy sector, offering numerous advantages such as reducing human exposure to hazardous tasks, enhancing predictive maintenance, and improving incident response times. These advancements not only safeguard employees but also contribute to operational efficiency and reliability across industries.

One of the primary benefits of automation is its ability to minimize human involvement in hazardous environments. By delegating dangerous tasks to machines, workers are shielded from exposure to toxic substances, high temperatures, and physically demanding conditions. Electrical automation technologies employed in power plants monitor equipment status and provide timely alerts for operational issues, reducing the need for human intervention in perilous scenarios. Such systems not only enhance safety

but also ensure continuous monitoring and quick resolution of potential problems.

Predictive maintenance, enabled by automation, has significantly improved operational safety and efficiency. Advanced systems utilize real-time data to predict equipment failures and schedule maintenance proactively, thereby preventing accidents and minimizing downtime. Programmable logic controller (PLC) technology facilitates the real-time monitoring of power equipment, enabling efficient diagnostics and energy-saving measures while maintaining a high standard of safety in energy operations. Furthermore, predictive maintenance reduces the financial and human costs associated with unexpected equipment failures.

Automation also enhances incident response times by leveraging advanced technologies to detect and address safety concerns swiftly. Emergency automation systems are designed to monitor power systems, process unsafe conditions, and implement corrective actions instantaneously. These systems ensure stability and safety in critical energy operations by utilizing IoT-enabled devices for rapid data acquisition and response. Similarly, augmented reality (AR) applications in safety protocols provide workers with real-time visual cues, enabling them to react promptly to potential hazards.

The implementation of automation in safety processes is complemented by international standards and frameworks that ensure compliance and operational consistency. The adoption of safety-related control systems guided by global frameworks has revolutionized the energy sector by integrating programmable electronics into safety functions. This evolution has greatly improved the safety integrity of automated systems, ensuring that critical operations remain within acceptable parameters.

Despite these benefits, the integration of automation technologies must address challenges such as system reliability and cybersecurity vulnerabilities. These challenges underscore the importance of rigorous design and continuous monitoring of automated systems to sustain their effectiveness in enhancing safety. Nonetheless, the benefits of automation in reducing exposure to hazards, enabling predictive maintenance, and expediting incident responses remain unparalleled in the energy sector.

3.2. Challenges in Implementing Automation for Safety:

Identification of challenges, including technological integration costs, skill gaps in the workforce, and managing the transition from manual to automated systems.

The integration of automation in industries, particularly within the context of safety, holds substantial promise for improving operations. However, it also presents significant challenges, particularly regarding technological integration, workforce adaptation, and the transition from traditional manual systems. This section explores the complexities involved in implementing automation for safety, highlighting both the benefits and challenges associated with its adoption. A central challenge in automation is the high cost of technological integration. The expense of designing and implementing automation systems can be formidable, particularly for industries such as energy, where safety-critical processes must be automated to mitigate risks. For instance, in the Floating LNG (FLNG) 1 project, one of the most ambitious and risky projects ever undertaken in recent years, the integration of safety and automation systems was

complex and costly. The project required a substantial number of safety sensors and automation systems, far exceeding the typical requirements for facilities of similar size. Given the lack of reference for such projects, the FLNG 1 team had to develop and thoroughly appraise these systems to ensure high safety integrity while maintaining the operational availability of the facility (Dahlan, 2018)^[8]. These high costs can deter companies from adopting automation, especially in the early stages when the return on investment (ROI) is not immediately apparent.

Another significant barrier to the successful implementation of automation in safety is the skill gap in the workforce. As automation systems become more complex, the workforce must be trained to handle these advanced technologies effectively. Many workers may not have the technical expertise required to operate or maintain automated systems, which can lead to a dependency on a smaller, more specialized workforce. This issue is particularly pronounced in industries such as oil and gas, where the transition to automation requires not only new skills but also a fundamental shift in how safety is perceived and managed. As noted by Oglesby et al. (2014)^[27], the interaction between human operators and automated systems must be carefully considered to ensure that safety and efficiency are maximized. Without adequate training, the workforce may struggle to adapt, which could compromise both safety and productivity.

The transition from manual to automated systems presents additional challenges. Many industries, particularly those in the energy sector, have long relied on manual systems and processes. Moving from these traditional methods to automated systems requires significant adjustments not only in the technical infrastructure but also in organizational culture. Resistance to change is common in such transitions, as workers and managers may fear job displacement or feel uncertain about the reliability of automated systems. Furthermore, automated systems introduce new types of risks that were previously unknown, creating a need for continuous oversight and adaptation. For example, Huffman (2015)^[15] explored the role of automation in improving process safety, noting that while basic automation can enhance the ability to maintain processes within acceptable limits, it also requires new approaches to monitoring and intervention. The lack of historical precedent for automated systems can make the transition even more challenging, as teams must devise entirely new strategies to address unforeseen risks.

Moreover, the integration of automation often leads to new types of safety risks. While automation can reduce human exposure to hazardous tasks, it also introduces complexities in the systems that manage these tasks. Automation in environments like oil and gas or renewable energy must account for a wide range of factors, including the reliability of sensors, the potential for system failure, and the possibility of unforeseen interactions between automated components. In the case of the FLNG 1 project, the unique combination of marine, subsea, and process systems required that safety and automation systems be designed to ensure high integrity without compromising the operational availability of the facility (Dahlan, 2018)^[8]. These considerations highlight the importance of thoughtful system design to mitigate new risks introduced by automation.

Despite these challenges, the integration of automation in safety systems offers considerable benefits. Automation can enhance predictive maintenance by using sensors and

monitoring systems to detect early signs of equipment failure before it results in catastrophic incidents. This capability not only reduces the frequency of accidents but also improves the overall efficiency of operations. Automation can also drastically improve incident response times. Automated systems can detect abnormalities more rapidly than human operators, allowing for faster responses to emerging issues, such as equipment malfunctions or hazardous conditions. By reducing human error and improving the precision of response mechanisms, automation contributes to safer and more reliable operations across energy sectors (Vagaš et al., 2018) ^[35].

While the implementation of automation for safety in industries such as energy presents a host of challenges, including technological costs, workforce skill gaps, and the transition from manual to automated systems, it also offers substantial benefits. These benefits include improved predictive maintenance, faster incident response times, and enhanced safety by reducing human exposure to hazardous tasks. However, overcoming the barriers to automation requires careful planning, investment in workforce training, and an ongoing commitment to system evaluation and improvement. As industries continue to evolve, it will be crucial to balance the benefits of automation with its associated challenges to achieve the optimal level of safety.

3.3. Strategic Solutions for Balancing Risks and Benefits:

Insights into strategies to address challenges, such as fostering workforce training, implementing fail-safe systems, and adopting hybrid human-machine models.

Automation in safety-critical systems has brought significant advancements in operational efficiency and risk mitigation. However, balancing the risks and benefits of automation necessitates strategic solutions, including workforce training, fail-safe system implementation, and hybrid human-machine models. These approaches ensure that the integration of automation enhances safety without introducing unmanageable risks.

Workforce training is a cornerstone of balancing automation's benefits with its inherent challenges. As automation systems grow increasingly sophisticated, workers must be equipped with the necessary skills to operate and maintain these technologies effectively. Training programs focused on technical and cognitive skills are crucial in ensuring that human operators can collaborate with automated systems. For instance, Cook et al. (2018) ^[38] emphasize the importance of synergy between human operators and machines, as over-reliance on automation can lead to misunderstandings and potentially hazardous situations. Training initiatives that address these challenges can empower workers to utilize automation responsibly while mitigating risks associated with human error (Cook et al., 2018) ^[38].

Fail-safe systems are another critical component of effective automation strategies. These systems are designed to maintain safety even in the event of equipment failure or human error. By integrating multiple layers of safety controls, fail-safe mechanisms ensure that operations remain within acceptable limits, preventing catastrophic incidents. Huffman (2015) ^[12] discusses the role of sequential automation in maintaining process safety, noting that thoughtful system design can prevent conditions requiring emergency interventions. The implementation of such systems reduces the likelihood of accidents, ensuring that

safety remains a priority even under challenging circumstances (Huffman, 2015) ^[12].

Adopting hybrid human-machine models further enhances the balance between automation's risks and benefits. These models integrate human oversight with automated processes, ensuring that critical decisions are informed by human judgment while routine tasks are managed by machines. Ishigooka et al. (2022) ^[14] introduce the concept of "Symbiotic Safety," where action plans and safety rules dynamically adapt to optimize collaboration between humans and machines. This approach minimizes risks while maintaining operational , particularly in autonomous systems, where automated processes must comply with stringent safety requirements. These frameworks enable continuous evaluation and adaptation, ensuring that risks are managed proactively (Machin et al., 2018) ^[39].

Balancing the risks and benefits of automation requires a multifaceted approach that includes comprehensive workforce training, robust fail-safe systems, and hybrid human-machine models. By adopting these strategies, industries can harness the advantages of automation while mitigating potential risks, ensuring that safety and efficiency coexist harmoniously.

4. Future Directions

4.1. Emerging Trends in Automation and Worker Safety:

Speculation on future trends, including AI-driven safety analytics, enhanced machine learning algorithms for risk prediction, and real-time safety monitoring through IoT integration.

Emerging trends in automation and worker safety are poised to revolutionize industry practices through advanced technologies such as AI-driven safety analytics, enhanced machine learning algorithms for risk prediction, and real-time safety monitoring facilitated by IoT integration. These innovations offer the potential to not only mitigate workplace risks but also create more adaptive and resilient safety systems.

AI-driven safety analytics represents a transformative development in understanding and preventing workplace accidents. Advanced systems analyze historical safety data to identify patterns and predict potential risks before they manifest. This predictive capability underscores the role of AI in preemptively addressing safety concerns, thereby enhancing decision-making processes in labor protection management.

Enhanced machine learning algorithms further elevate risk prediction capabilities by adapting to dynamic workplace conditions. These systems utilize extensive datasets to refine their understanding of safety risks and propose tailored interventions. For example, deep learning models have been integrated into factory safety monitoring systems to ensure the proper usage of protective equipment, directly reducing accident rates. Such systems exemplify how machine learning can contribute to maintaining compliance with safety protocols while fostering a culture of accountability. IoT integration complements these advancements by enabling real-time monitoring and communication across safety-critical operations. IoT devices, equipped with sensors and connectivity features, collect and transmit data on environmental conditions, equipment status, and worker behavior. The enhancement of systems with IoT technology demonstrates how GPS tracking and biometric verification can ensure adherence to safety protocols before commencing

hazardous tasks. Such innovations mitigate human errors and provide actionable insights into improving operational safety. As these technologies mature, the synergy between AI, machine learning, and IoT is expected to define the future of worker safety. Analytical approaches, such as data mining to assess occupational risks using injury safety indicators, further emphasize the potential of data-driven insights to enhance workplace safety. By integrating these methodologies into comprehensive safety platforms, industries can achieve real-time decision-making and proactive risk management.

The future of automation and worker safety is centered on leveraging advanced technologies to predict, monitor, and mitigate risks dynamically. By adopting AI-driven analytics, refining machine learning algorithms, and embracing IoT-enabled systems, industries can foster safer working environments and adapt to evolving safety challenges. These trends hold the promise of reshaping safety standards and setting new benchmarks for proactive risk management in diverse industrial landscapes.

4.2. Opportunities for Safer Work Environments:

Exploration of opportunities to improve safety and productivity by advancing automation technologies, fostering industry collaboration, and enhancing regulatory frameworks for automated operations.

The advancement of automation technologies presents significant opportunities to improve safety and productivity in industrial operations. By fostering industry collaboration and enhancing regulatory frameworks, stakeholders can address challenges and unlock the potential of automated systems to create safer work environments.

Emerging automation technologies such as collaborative robots (cobots) and safety-integrated systems play a crucial role in advancing safety standards. Cobots, designed to work alongside humans, require robust safety protocols and compliance with industry standards to ensure their effectiveness. These systems not only enhance productivity but also mitigate risks in shared workspaces, emphasizing the importance of continual refinement of safety measures. In industrial automation, leveraging collaborative technologies fosters innovation and reinforces the commitment to secure and efficient operations.

Industry collaboration serves as a cornerstone for promoting safer automation practices. Collaborative efforts across sectors enable the sharing of expertise and the development of best practices tailored to unique operational environments. For instance, integrated management systems that combine safety training and accessible educational resources have demonstrated improved compliance with safety standards, while fostering a culture of shared responsibility. Such approaches highlight the value of partnership in driving progress in workplace safety initiatives.

Regulatory frameworks also play a pivotal role in ensuring the safe deployment of automation technologies. By integrating updated safety standards, such as Safety Integrity Level (SIL) protocols, regulatory bodies provide a structured approach to addressing the complexities of automated operations. These frameworks not only enforce compliance but also encourage innovation by setting clear benchmarks for system design and implementation. The alignment of automation technologies with regulatory requirements strengthens the foundation for secure industrial operations, reducing risks associated with equipment failure or system

vulnerabilities.

Further opportunities lie in the integration of digital technologies into safety management. For example, the adoption of IoT devices and AI-based systems enables real-time monitoring and adaptive responses to dynamic industrial conditions. By collecting and analyzing data on operational hazards, these technologies facilitate predictive maintenance and proactive risk management. Enhanced safety measures, supported by such innovations, demonstrate the potential for automation to transform traditional approaches to industrial safety.

Advancing automation technologies, fostering industry collaboration, and enhancing regulatory frameworks collectively offer transformative opportunities to improve safety and productivity. By embracing these strategies, industries can create secure and efficient work environments, paving the way for sustainable progress in automated operations.

Conclusion

Automation has emerged as a pivotal force in reshaping industrial safety, offering transformative benefits while presenting unique challenges. Across various sectors, automation has demonstrated its ability to enhance operational safety by reducing human exposure to hazardous tasks, enabling predictive maintenance, and improving incident response times. These advancements have not only safeguarded workers but have also contributed to greater operational efficiency and reliability. However, the integration of automation into safety-critical operations is not without complexity, as it introduces new risks, including over-reliance on technology, cybersecurity vulnerabilities, and skill gaps within the workforce.

The research underscores the importance of strategic solutions to balance the benefits and risks of automation. Workforce training emerges as a critical factor in ensuring that employees are equipped to handle advanced technologies effectively. Comprehensive training programs enable workers to adapt to the evolving demands of automation, fostering a synergy between human expertise and machine precision. Additionally, the implementation of fail-safe systems provides a robust safety net, ensuring that automated processes maintain integrity even in the face of technical failures or human errors. Hybrid human-machine models further enhance this balance by integrating human oversight into automated systems, leveraging the strengths of both to maintain safety and adaptability.

Emerging trends in automation, such as AI-driven safety analytics, enhanced machine learning algorithms, and IoT-based real-time monitoring systems, highlight the potential for transformative advancements in worker safety. These technologies enable predictive insights, adaptive responses, and dynamic risk management, significantly reducing workplace hazards. By embracing such innovations, industries can create safer and more resilient operational environments. However, the successful implementation of these technologies requires careful consideration of regulatory frameworks and collaborative efforts to ensure alignment with safety standards and best practices.

Opportunities for further advancements in automation and worker safety lie in fostering industry collaboration and enhancing regulatory frameworks. Collaborative efforts among stakeholders promote knowledge sharing and the development of industry-wide best practices, which are

essential for addressing the multifaceted challenges posed by automation. Enhanced regulatory frameworks provide a structured approach to managing safety risks, setting benchmarks for system design and operational compliance. Together, these efforts create a foundation for sustainable progress in automated safety systems.

Automation represents a significant opportunity to revolutionize worker safety while enhancing productivity and operational efficiency. The benefits of automation, when effectively harnessed, outweigh its challenges. Strategic solutions such as workforce training, fail-safe mechanisms, and hybrid models offer pathways to mitigate risks and optimize safety outcomes. By embracing emerging trends and fostering collaboration and regulation, industries can navigate the complexities of automation with confidence. The future of automation in safety is promising, offering the potential to redefine industrial practices and establish new standards for protecting workers in an increasingly automated world.

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