Sustainability Risk Assessment in Pipeline Infrastructure Systems

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The secure and dependable functioning of pipeline infrastructure systems is pivotal for transporting vital energy resources during this transition era towards a more sustainable energy future. The importance of pipeline risk management in ensuring the secure and dependable transportation of crucial resources has attracted considerable attention.

energy pipeline infrastructure risk sustainability

1. Introduction

In an era driven by rapid technological advancements and ever-increasing demand for energy resources, pipeline infrastructure systems play a pivotal role in facilitating the transportation of crucial commodities, such as oil and gas, by connecting producing areas to refineries, chemical plants, consumers, and other business areas [1]. While these pipeline systems form the lifeline of modern societies, they also face a myriad of challenges, ranging from natural disasters [2] and mechanical failures [3] to human-induced incidents and security threats [1][4]. To ensure the robustness and sustainability of pipeline infrastructures, a comprehensive understanding of sustainability risk has become an imperative part of pipeline operations and maintenance policies [5].

The importance of pipeline risk management in ensuring the secure and dependable transportation of crucial resources has attracted considerable attention. Kraidi et al. (2021) crafted a risk management strategy, examined risk factors, and assessed risk mitigation methods in oil and gas pipelines [6]. Additionally, studies, such as those introducing intelligent control strategies for multiphase pipelines in oilfields [7], underscore the significance of enhancing operational efficiency and safety, aligning with the broader trend of developing smart pipelines through data analysis and automated systems. These efforts collectively contribute to ensuring the safety and effectiveness of critical energy infrastructures. The integration of risk assessment, mitigation, and response strategies into pipeline operations is essential for preventing incidents and minimizing their impact. Risk is characterized by the combination of scenarios, frequency, and potential negative outcomes of events [8]. Risk assessment planning is critical for effectively managing pipeline data. Conducting comprehensive risk assessments helps identify potential hazards and vulnerabilities, which enables stakeholders to prioritize and implement targeted risk mitigation strategies [9]. This ensures the protection of the environment, enhances public safety, and optimizes resource allocation.

Over time, risk assessment methodologies have advanced to encompass diverse risk dimensions. In the transitional phase towards a more sustainable energy future, there arises a necessity to shift from conventional risk management frameworks to those that encompass a broader spectrum of sustainability considerations. Indeed, incorporating sustainable approaches into risk assessment ensures that the energy infrastructure is designed and operated in an environmentally responsible and socially equitable manner, along with economic significance. A comprehensive framework was introduced by Mahmood et al. (2023) to integrate social, environmental, and economic dimensions into risk, reliability, and resilience analysis with a goal of fostering sustainable pipeline infrastructure [10]. Furthermore, incorporating Sustainable Development Goals (SDGs) into risk management practices is paramount, ensuring that risk mitigation aligns harmoniously with broader societal objectives [11]. This heightened emphasis on integrating sustainability principles is driven by the growing recognition of the intricate interplay between environmental, social, and economic dimensions within risk management processes and underscores the alignment with the United Nations SDGs [12].

2. Sustainability Risk Assessment in Pipeline Infrastructure Systems

The energy distribution infrastructure in the United States (US) comprises an extensive network of pipelines spanning more than 2.5 million miles [13]. Thus, a meticulously managed and well-protected pipeline network guarantees the uninterrupted flow of energy resources, mitigating the potential for supply disruptions, which is crucial for pipeline infrastructure. Numerous significant accidents bear witness to the magnitude of major explosions and hazardous toxic releases, imposing severe economic and environmental repercussions [14]. These incidents underscore the critical need for robust safety measures and risk management strategies within the realm of pipeline systems to prevent and mitigate such detrimental impacts.

According to Girgin and Krausmann (2016), analyzing historical incident data can unveil the fundamental triggers, failure modes, associated outcomes, and statistical trends of these significant disruptions [2]. Concentrating on natural hazard triggers, this research analyzed incidents involving onshore hazardous liquid pipelines. This historical analysis allowed a better understanding of incident mechanisms and helped the preparation of prevention and mitigation measures. Sovacool (2008) conducts an introductory assessment of societal and economic impacts linked to major energy-related accidents occurring between 1907 and 2007, highlighting the noteworthy aspects of fatalities, property damage, and frequency of occurrence [15]. In their study, Biezma et al. (2020) gathered the ten deadliest events in the history of oil and pipeline accidents to investigate the underlying factors in order to elevate the safety and advancement of the oil and gas pipeline transportation network [16]. Ramírez-Camacho et al. (2017) highlighted through a retrospective examination of 1063 onshore pipeline accidents the potential hazards of accidental containment and substantial consequences for populated areas, impacting people, equipment, and the environment [17]. The study by Restrepo et al. (2009) examined the causes and costs of accidents in US hazardous liquid pipelines, employing regression modeling to assess financial repercussions and offer insights to industry leaders for managing risks and allocating resources [18]. Similarly, Siler-Evans et al. (2014) examined US natural gas and hazardous liquid pipeline accidents, revealing decreased fatalities and injuries and increased property damage over time [19].

Various scholarly works have explored diverse aspects of quantitative risk analysis. Han and Weng (2010) introduced a comprehensive quantitative approach to assess risk within pipeline networks, encompassing probabilistic accident assessment, consequence analysis, and risk evaluation [20]. Probabilistic and deterministic approaches to pipeline corrosion risk assessment were compared by Lawson (2005), with an emphasis on the benefits of the probabilistic method in handling uncertainties and potentially optimizing risk management [21]. Risk analysis methodologies in pipeline applications often extend to include structural reliability assessment, data analysis, and decision-making tools to enhance the robustness of pipeline systems [22]. Some of the most recent developments in risk assessment of pipeline infrastructure are as follows. Li et al. (2022) proposed a risk assessment framework that considers uncertainty for corrosion-induced pipeline accidents as a pair of limit state functions and was solved by the Monte Carlo approach [23]. He et al. (2023) employed a quantitative risk assessment method based on the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE) for a hot work pipeline infrastructure [24]. Liang et al. (2023) developed a risk assessment model for cascading failures that includes the calculation of the probability and severity of the cascading failure chain [25]. Additionally, quantitative risk models [10], such as hazard and operability (HAZOP) analysis [26], failure mode, effects, and critical analysis (FEMA/FMECA) [27], fault tree analysis (FTA) [28], bowtie analysis [29], or the Bayesian network-based approach [30], have been proposed and employed as risk assessment approaches in pipeline applications.

To complement the risk assessment efforts, several existing sustainability assessment frameworks and indices, such as United Nations SGDs, Global Reporting Initiative (GRI), and Environmental, Social, and Governance (ESG) Ratings, provide overviews of sustainability performance across various dimensions. These frameworks help organizations, governments, and stakeholders associated with the pipeline infrastructure systems to assess their sustainability efforts and make informed decisions. The United Nations SDGs are a set of 17 global goals adopted by United Nations member states to address social, economic, and environmental challenges, covering areas such as poverty, health, education, clean energy, climate action, and more [31]. The GRI offers organizations guidelines and metrics to report sustainability performance, facilitating stakeholders to comprehend sustainability impacts and commitments [32]. ESG Ratings are often employed to measure the impact of sustainable investments, with a typical score ranging from 0 to 100, and a score of 70 and above being considered good [33]. While these are valuable frameworks for measuring sustainability and assessing the social, environmental, and ethical performances of organizations, they are not typically used as direct tools for measuring sustainability risk.

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