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Fossil Energy Resilience in a Changing Climate: Risk Analysis, Strategies, and Practical Plan

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Abstract. Climate change is a global phenomenon driven by increased greenhouse gas (GHG) emissions, resulting in various environmental impacts. Its effects include increasing global temperatures, which manifest as tangible physical risks such as sea-level rise, land subsidence, and extreme weather events. These phenomena can damage infrastructure, trigger oil spills, contribute to environmental pollution, and generate other detrimental impacts. Numerous studies emphasize that the physical risks posed by climate change have become a central focus in sustainable management within the oil and gas (O&G) industry. The O&G is projected to remain a necessary component of the energy mix for several decades, alongside the development of new and renewable energy (NRE), to ensure national energy security during the transition toward Net Zero Emissions (NZE). This study adopts a qualitative approach to examine the resilience of the O&G industry in addressing climate-related risks. The findings include a risk analysis framework, the development of physical and policy strategies, and potential adaptation scenarios implementable by the industry. These results highlight the urgency of proactive climate adaptation efforts to ensure the long-term sustainability of the O&G sector in the coming decades while supporting Indonesia's transition to NZE.

1 Introduction

Fossil energy will remain a crucial requirement in the future, making sustainable investments essential to prevent potential energy supply shortages [1]. As of 2023, fossil fuels continued to dominate global energy consumption, accounting for approximately 81.5% of the total energy mix worldwide [2]. The combustion of fossil fuels results in significant CO_2 emissions, which contribute to climate change by increasing the Earth's surface temperature. One of its primary indicators is the rise in global average surface temperature, which reached 1.1 °C higher during the 2011–2020 period compared to pre-industrial levels (1850–1900) [3]. This warming trend is driven by human activities that generate greenhouse gas emissions [3-4]. Current emission trajectories continue their upward trend, with the oil and gas sector being one of the primary contributors. Recent data reveal that oil and gas production,

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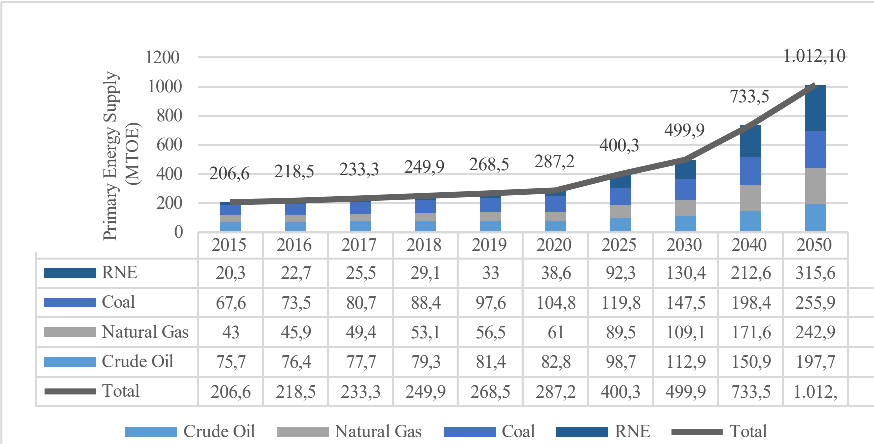
transportation, and processing accounted for approximately 5.1 billion tons of greenhouse gas emissions, equivalent to roughly 15% of global energy-related emissions in 2022 [1]. This makes the energy sector one of the industries facing urgent decarbonization demands to meet the Paris Agreement targets of achieving global emission reductions.

Operational activities in the oil and gas sector are significant contributors to greenhouse gas emissions. Nevertheless, Figure 1 explains that fossil energy is still required to meet the national energy demand in the future, as outlined in the National Energy Policy (RUEN). Projections indicate fossil fuels will account for 369.5 MTOE by 2030, compared to 130.4 MTOE from renewable energy. This trend persists through 2040 (520.9 MTOE) and 2050 (696.5 MTOE), demonstrating that oil and gas will maintain vital importance for national energy security during the clean energy transition in the coming decades [5].



	2015	2016	2017	2018	2019	2020	2025	2030	2040	2050
RNE	20,3	22,7	25,5	29,1	33	38,6	92,3	130,4	212,6	315,6
Coal	67,6	73,5	80,7	88,4	97,6	104,8	119,8	147,5	198,4	255,9
Natural Gas	43	45,9	49,4	53,1	56,5	61	89,5	109,1	171,6	242,9
Crude Oil	75,7	76,4	77,7	79,3	81,4	82,8	98,7	112,9	150,9	197,7
Total	206,6	218,5	233,3	249,9	268,5	287,2	400,3	499,9	733,5	1.012,

Figure 1. Indonesia's Projected Energy Mix

Fossil fuels are expected to remain essential through 2050–2060 during the transition toward renewable energy. The accumulation of CO_2 emissions over recent decades has accelerated climate change and significantly impacted oil and gas facilities, which have become increasingly vulnerable to various climate change-related risks [6]. Rising global surface temperature triggers multidimensional risks, including sea-level rise, extreme weather events, droughts, land subsidence, and intensified precipitation, which pose significant threats to oil and gas infrastructure, including both offshore and onshore facilities, compromising long-term energy security [7-8]. These climate risks pose substantial threats to operational continuity, including infrastructure degradation, production disruptions, supply chain vulnerabilities, increased spill risks, occupational health and safety hazards, and escalating financial liabilities caused by emergency maintenance costs, unplanned downtime, and climate adaptation retrofitting [7-8].

Several scientific studies have examined the effects of climate change on oil and gas infrastructure. Findings suggest that climate change may increase the risk of oil spills and lead to significant damage to large-scale infrastructure [6]. However, most existing studies remain limited in scope and therefore do not provide a comprehensive understanding of the sector's overall vulnerability. This study aims to address this gap by presenting a more comprehensive analysis and proposing more detailed strategies by offering alternative approaches for the application of climate change adaptation and mitigation measures, particularly for companies operating in the fossil energy sector.

Amid escalating climate-related disruptions, the oil and gas industry must establish comprehensive multi-decadal planning frameworks to ensure the continuity of fossil fuel

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operations. This study aims to assess climate-related risks to oil and gas infrastructure, formulate integrated physical and transitional strategies with corresponding policy recommendations, and propose practical implementation scenarios for industry adoption.

2 Methodology

This study conducts a qualitative analysis, synthesis, and examination of information through a desk review, related to the close relationship between climate change issues and the oil and gas industry, to provide an understanding of the projected needs of countries for fossil energy, impacts, challenges, and risks faced by the oil and gas industry in Indonesia; as well as strategies that can be implemented in the context of climate change issues.

Currently, there is no standardized methodology or official guideline for conducting a desk review. Nevertheless, this approach serves as an alternative method that allows for the integration of rigor and comprehensiveness, while also accommodating the complexity and diversity of available sources [9]. Data is collected from a variety of reliable sources, including academic databases such as ScienceDirect and Google Scholar, international and national climate-related policies, reports from leading organizations such as the IPCC and IEA, and data from the Ministry of the Republic of Indonesia.

Figure 2 illustrates the methodological flowchart adopted in this study, developed with reference to prior studies on desk review approaches [9]. The sources were selected based on two main criteria: (1) relevance to the study discussion, and (2) the credibility of the source, where only publications issued by trusted institutions or academic/industry databases are used. The data was extracted to adjust aspects of the study, such as the background of the issue of future fossil energy needs, the infrastructure of oil and gas companies that are vulnerable to the impacts of climate change, and what strategies oil and gas companies need to implement for business sustainability, while still supporting the achievement of NZE. All data were then categorized and systematically compiled to cover aspects of the study. Ethically, the study also provides appropriate acknowledgment and reference to the original sources and authors cited in the analysis process.

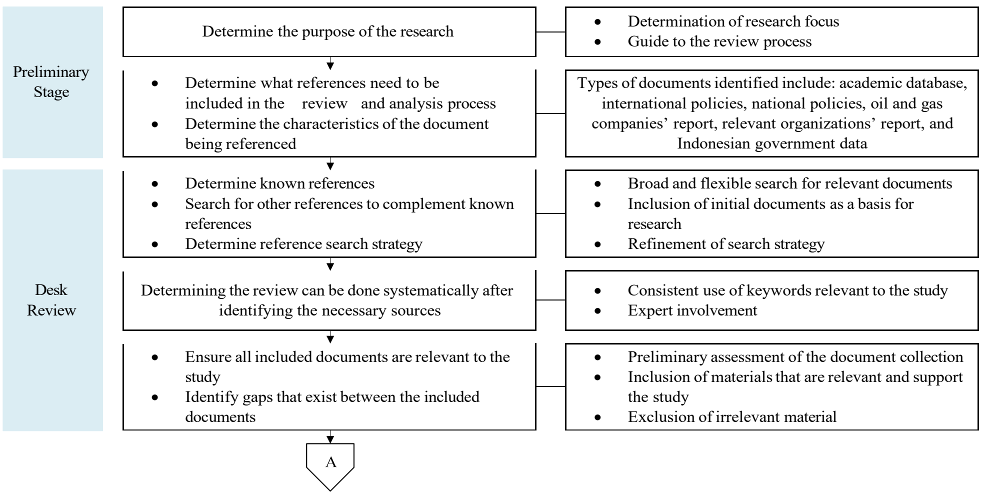

Figure 2. Flowchart for Research Methodology

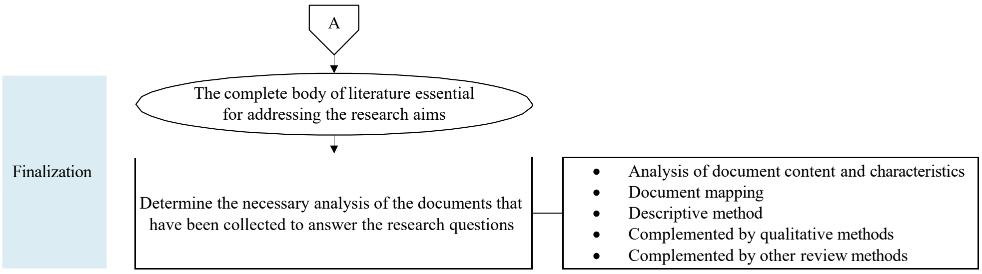

Figure 2. Flowchart for Research Methodology (Continued)

3 Results and discussion

3.1 Assessment of NZE achievements and vulnerability of oil and gas infrastructure

Following the pandemic period, Indonesia has experienced an accelerated growth in greenhouse gas emissions, with the energy sector demonstrating particularly concerning trends. In 2022, energy-related emissions surged by 21% year-on-year, reaching 715 million metric tons of CO2 equivalent (MtCO2e) [10]. The adoption of renewable energy remains significantly below target due to insufficient commitment and leadership in establishing effective policy frameworks to accelerate the transition [10]. Indonesia's energy sector has consistently represented the primary source of greenhouse gas (GHG) emissions since 2020, demonstrating a persistent upward trajectory. The Climate Action Tracker (CAT) rates Indonesia's climate targets and policies as 'Critically Insufficient' [11]. Indonesia's commitments project an emissions trajectory consistent with a warming scenario exceeding 4°C. This assessment indicates that the ambition of Indonesia's climate policy framework remains inadequate and misaligned with the Paris Agreement's 1.5°C threshold target [11]. According to emission data reports from Indonesia's Ministry of Environment and Forestry (KLHK), the period from 2020 to 2024 demonstrates consistently high and rising emissions from the energy sector [12]. This condition has contributed to a five-year delay in achieving emission reduction targets [13]. Consequently, it can be concluded that fossil fuel energy (oil and gas) remains the dominant energy source in Indonesia's current energy mix [12, 14].

Climate change presents significant risks to the operational continuity and long-term sustainability of the oil and gas sector. Current estimates indicate that approximately 40% of global oil and gas reserves face substantial threats from the physical impacts of climate change [7]. Table 1 presents an example that shows climate change events can cause global oil and gas infrastructure to be damaged or disrupted, resulting in oil spills, company reputation issues, collapses, disruptions to the supply chain, environmental pollution, and disasters to communities [7].

Table 1. Some of the climate change events impacting the oil and gas industry

Event	Location	Period	Climate Impact
Hurricane Ida	Louisiana, United States	2021	• An oil spill occurred in the Gulf of Mexico. • 88% of offshore oil production was halted. • Over 100 oil drilling facilities were rendered inoperable. • Market losses amounted to 17.5 million barrels of oil up to September 2021. • The total estimated loss ranged from US$25 billion to US$35 billion.

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Event	Location	Period	Climate Impact
Water-related issues, such as drought, extreme heat, and water scarcity	Large oil & gas companies operating in the US	2016	• Impact on oil and gas production processes due to water requirements. • Increased health and safety risks for workers in the workplace, potentially leading to decreased productivity. • 57% of the 110,000 oil and gas wells in the US are damaged. • 9 of the top 10 oil companies in the US operate 70% or more of their wells in areas with moderate or high water scarcity.
Shifting ice sheets in Russia	Norilsk, Russia	2020	• The melting of the ice sheet weakened the foundation of the storage tank, causing 20,000 tons of diesel to leak into the river. • 45% of Arctic hydrocarbon extraction fields in Russia have the potential to be damaged by 2050, and 40% of the Trans-Alaska Pipeline System (TASP) in the United States is similarly affected. • Russia's physical infrastructure in the Arctic, worth about US$250 billion, is threatened by the melting of permafrost.
Wildfires in Alberta	Alberta, Canada	2015	• 10% of oil and gas production ceased. • Canadian Natural and Cenovus suspended their operations for safety reasons. • Production losses ranged from 80,000 to 135,000 barrels per day.
Wildfires in Fort McMurray	Fort McMurray, Canada	2016	• Production declined by up to 40%, resulting in a reduction of nearly 1 million barrels per day in output. • 665 worker accommodation camp units were destroyed by fire.

In 2021, Hurricane Ida caused a record 55 oil spills in the Gulf of Mexico, severely damaging offshore oil and gas infrastructure, disrupting crude oil supply chains, and resulting in significant economic losses. Between 2011 and 2016, several oil and gas wells in the United States were situated in areas categorized as experiencing extremely high water stress. In 2020, thawing permafrost in Norilsk, Russia, compromised the structural integrity of a fuel storage tank, leading to infrastructure failure, disruption of transport networks, and considerable financial losses. Similarly, major wildfires in Alberta and Fort McMurray, Canada, in 2015 and 2016, had a substantial impact on oil sands operations, reducing production levels and temporarily halting a significant portion of the region's output [7].

Given Indonesia's geographical status as an archipelago nation rich in oil and gas resources, numerous upstream and downstream activities are highly susceptible to the impacts of climate change. Should these impacts materialize, there is a substantial risk of infrastructure collapse and disruptions to the national energy supply. Consequently, long-term strategies are imperative for predicting and analyzing the effects of climate change on both onshore and offshore infrastructure.

3.2 Risk analysis

The physical risks that occur are direct risks from climate change, including risks to facilities and infrastructure, impacts to operations, water and raw materials, and disruptions to supply chains [8]. Table 1 presents data on physical infrastructure damage resulting from climate change phenomena, which serves as empirical evidence that climate change has produced tangible impacts in the field. This study then proceeds with a risk analysis, explained in Table

2, employing a climate event parameter based approach, adapted from previous research. These climate event parameters serve as the foundation for identifying risks and assessing their potential impacts in a general context.

Table 2. Risk analysis of climate change impacts on oil and gas infrastructures

Climate Change Events	Risk Identification	Impact
Sea Level Rise, Land Subsidence, Lightning Strikes, Landslides, Storms, and Flood	Disruption of road access	• Disruption of plant operations • Risk of logistics or operational delays • Workplace accidents due to slippery roads and inundation
	Interference with electrical systems	• Potential damage to electrical systems • Operational shutdown
	Continuous exposure of facility structures to inundation	• Disruption of business activities or supply chains • Pipeline leaks/spills • Degradation of facility structures, potentially leading to collapse • Corrosion of materials or structures • Detrimental impact on the company's image among the public and globally • Compensation and/or legal issues • Fires • Increased maintenance and repair costs
	Collapse of equipment, facilities, or installations	• Disruption of business activities or supply chains • Oil spills • Detrimental impact on the company’s image among the public and globally • Compensation and/or legal issues • Fires • Increased maintenance and repair costs
	Lightning strikes on equipment, facilities, or installations	• Disruption of business activities or supply chains • Oil spills • Detrimental impact on the company’s image among the public and globally • Compensation and/or legal issues • Fires • Increased maintenance and repair costs
	Open access due to inundation potentially reduces plant perimeter control	• Disruption of business activities or supply chains • Theft or loss of assets • Operational disruptions • Oil spills • Fires • Detrimental impact on the company’s image among the public and globally • Compensation and/or legal issues • Increased maintenance and repair costs
	Disruption of waste management facilities	• Oil spills • Ecosystem contamination • Deterioration of company image/reputation • Compensation and legal issues

From Table 2, it is evident that climate change poses significant threats to oil and gas infrastructure. This phenomenon disrupts operations through physical damage, safety hazards, environmental and legal liabilities, and security risks. Proactive adaptation and mitigation strategies, incorporating enhanced designs, advanced monitoring, robust emergency plans, and extensive stakeholder collaboration, can effectively mitigate these disruptions.

3.3 Strategies

In response to the impacts of climate change, it is essential to identify deployable strategies for corporate mitigation and adaptation efforts. These strategies represent a concrete application of risk management phases aimed at bolstering infrastructure resilience, reducing climate exposure to physical risks, and anticipating disruptions to operational and business continuity. Table 3 outlines applicable strategies for oil and gas companies, categorized into physical & transition strategies and policy strategies. Physical & transition strategies encompass physical constructions as an adjustment effort due to climate change, alongside emission prevention and reduction through technology adoption, to achieve resilience and robustness [15]. Whereas policy strategies do not involve physical construction but rather utilize knowledge, practices, or agreements to reduce risks and disaster impacts. This is achieved particularly through the implementation of policies and laws, enhanced public awareness, training, and education [15].

Table 3. Strategies and policies for climate change impacts

Types of Strategies	Strategy	Explanation
Physical & transition strategies	Reinforcing Existing Infrastructure	Strengthening infrastructure involves engineering solutions such as building embankments or retaining walls, raising elevations, additional protection of electrical panels (waterproofing), and repairing structures with materials that are more resistant to corrosion.
	Relocating Facilities	Megaprojects to move critical infrastructure (e.g., refineries, terminals) to less vulnerable zones must consider lifecycle emissions, environmental impact assessments (EIAs), and stakeholder consent. Relocation reduces exposure but entails massive Capital Expenditure (CAPEX) and decommissioning liabilities. For instance, offshore platforms in hurricane-prone regions may be relocated, but this requires a robust cost-benefit analysis that integrates climate models and asset depreciation forecasts.
	Decommissioning (Asset Retirement) and/or Well P&A	Proactive well plugging and abandonment (P&A) and asset retirement mitigate environmental liabilities (e.g., leaks, spills) in flood-prone areas. Advanced monitoring can prioritize assets for decommissioning based on risk matrices. However, this strategy demands regulatory compliance and funding mechanisms to cover abandonment costs.
	Investing in Renewables and CCS/CCUS	Transitioning to renewable energy (e.g., offshore wind, solar-powered extraction) and carbon capture (CCS/CCUS) aligns with net-zero goals while leveraging existing expertise.
Policy strategy	Emergency Response Planning	A scientifically-grounded Emergency Response Plan (ERP) must incorporate: • Climate modeling to predict region-specific hazards (e.g., 50-year flood projections) • Scenario-based contingency planning for various climate events

Types of Strategies	Strategy	Explanation
		• Resource allocation matrices
	Training and Capacity Building	• Classroom and/or safety drill training • Virtual reality simulations for high-risk scenarios • Cross-functional emergency response teams • Regular competency assessments using standardized metrics
	Expanded Coordination Networks	• Establishing public-private early warning systems • Participating in global climate initiatives (e.g., OGCI, IPIECA) • Developing shared response protocols with local communities • Creating joint research programs with academic institutions
	Sustainability-Aligned Business Policies	• Science-based targets for emission reductions • Climate risk disclosure aligned with the financial report • Renewable energy investment roadmaps
	Supply Chain Optimization	• Alternative logistics routing scenarios • Supplier climate resilience assessments

Oil and gas companies are not only responsible for reducing carbon emissions but also for protecting their infrastructure and business continuity from the impacts of climate change. Table 4 details scenarios that these companies can consider for implementing physical and transition strategies. The selection of scenarios for executing these strategies is contingent upon the specific needs and available resources of the respective oil and gas company. This table was developed based on an analysis that considered various relevant factors within the context of climate change adaptation and mitigation in the fossil energy sector.

Table 4. Practical plan scenario

Scenario	Scenario 1: Joint Venture	Scenario 2: O&M Service	Scenario 3: Full Ownership	Scenario 4: Build-Operate-Transfer
Scope of Activities	Construction, Management, Operation, Maintenance, and Financing (Partially)	• Operation and Maintenance • The provision of facilities and financing is carried out by the government or other parties	• Construction, Management, Operation, and Maintenance • Fees are charged to the state or other parties through a fee scheme	Construction, Management, Operation, and Maintenance (Specific Time Frame)
Construction Implementa-tion	*Low Risk* The investment burden will be distributed to other companies	*Low Risk* Investment costs are borne by other parties (e.g., GOI)	*High Risk* The company bears the entire investment cost	*High Risk* The company bears the initial investment costs
Operations and Maintenance	*Medium Risk* The company is responsible for the operation and	*High Risk* The company is fully responsible for the operation and maintenance	*High Risk* The company is solely responsible for the operation	*High Risk* The company is fully responsible for the O&M for a

Scenario	Scenario 1: Joint Venture	Scenario 2: O&M Service	Scenario 3: Full Ownership	Scenario 4: Build-Operate-Transfer
	maintenance of part of the facility	of the entire facility	and maintenance of the entire facility	certain period, which is renewable
Opportunity	Full control of operations so that they get a good economy of scale	O&M cost efficiency	Owns all assets so that it can allocate other resources to more profitable projects/operations	The company can achieve project profitability by implementing pricing strategies that incorporate both cost recovery and appropriate profit margins
Risk	• Large capital expenditure on infrastructure and working capital • Highly susceptible to price changes	• Potential operational and maintenance problems that can lead to potential claims for damages (e.g., penalty)	• Construction, Management, Operation, and Maintenance • Fees are charged to the state or other parties through a fee scheme	• Initial investment risk • Risks to operating costs by the state or other parties affected by economic conditions

Table 4 presents various strategies for oil and gas companies to implement physical and adaptation measures, alongside considerations tailored to the company's needs and available resources. Based on a comparison of these scenarios, joint ventures or inter-company collaborations generally present a relatively lower risk compared to other options. However, the ultimate selection of a scenario is contingent upon the company's specific requirements and resource availability, with a thorough consideration of the risks and opportunities inherent in each.

4 Conclusion

The escalating impacts of climate change pose significant and multifaceted threats to Indonesia's O&G infrastructure, jeopardizing not only operational continuity but also national energy security and environmental sustainability. These vulnerabilities necessitate a paradigm shift from conventional risk management to a proactive, science-based framework for resilience.

To address these challenges, companies must adopt adaptation (physical) & transition strategies and policy strategies, including strengthening facilities, relocating facilities, decommissioning, investing in renewable energy sources, enhancing supply chain resilience, implementing ERP systems, providing workforce training, and fostering multi-stakeholder collaboration, such as government, institutions, and the community. Furthermore, practical plans for implementing adaptation and policy strategies can be pursued through four scenarios: full ownership, joint venture, operations and maintenance (O&M) service, and build-operate-transfer (BOT), which are selected based on organizational resources and capabilities.

Through such strategies, oil and gas companies can adapt to climate-related risks, maintain energy resilience, and advance their responsibility to reduce emissions while transitioning toward sustainable energy.

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