Fire disaster preparedness and risk management in critical energy infrastructure: A comprehensive assessment at Sei Gelam GEPP, Indonesia

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Abstract. Gas Engine Power Plants (GEPPs) are critical energy infrastructure, but their operation, involving combustible gases and high-voltage equipment, creates inherent fire hazards. This study offers a comprehensive analysis of fire disaster preparedness and risk management at the Sei Gelam GEPP, Jambi, Indonesia. Addressing a gap in location-specific industrial emergency readiness, this research uniquely integrates three assessment dimensions: Building Safety Reliability Value (BSRV), detailed fire management protocols, and worker preparedness. Employing a semi-qualitative approach with field observations, interviews, and questionnaires, the study provides a holistic safety ecosystem evaluation. Results indicate high readiness levels: the overall BSRV scored 96.34% ("Good"). Fire management units (role officers, firefighting teams, and coordinators) were also rated "Good" (scores of 100, 93, and 86, respectively). Furthermore, worker preparedness achieved a "Very Prepared" index value of 86. Despite these strengths, the analysis highlights specific areas for enhancement, including improving smoke exhaust systems, continuous competency development for fire control unit coordinators, and conducting more complex, realistic fire simulations. This research validates the facility's robust compliance while providing actionable, evidence-based recommendations for sustaining and enhancing emergency readiness in critical energy infrastructure.

1 Introduction

Fire incidents represent a significant human-made disaster with devastating consequences, including substantial material losses, prolonged operational disruptions, and tragic loss of life [1]. Globally, such events continue to pose substantial challenges, with Indonesia alone reporting 5,336 fire cases between May 2018 and July 2023, resulting in hundreds of billions of rupiah in economic losses and numerous fatalities [2]. Recognizing this pervasive threat, national regulations, such as Indonesian Law No. 28 of 2002 on Building Structures and Government Regulation No. 36 of 2005, mandate robust fire protection systems and emergency response protocols in all buildings, including industrial facilities like Gas Engine Power Plants (GEPPs).

GEPPs are vital components of Indonesia's energy infrastructure, with 193 such facilities distributed nationwide. They play a crucial role in meeting peak load demands and supplying electricity to remote areas. However, the inherent operational characteristics of GEPPs, involving flammable gases and high-voltage equipment, elevate their susceptibility to fire incidents. Historical data, including incidents at GEPPs in Tarakan and Sikka, underscore this vulnerability. The Sei Gelam GEPP in Jambi, with a 155 MW capacity, is pivotal for the Jambi region's energy supply, utilizing WARTSILA 20V34SG series engines known for high efficiency but demanding stringent safety measures. Potential fire hazards at this facility include gas leaks, electrical short circuits, and equipment overheating [3]. A severe fire incident at a similar GEPP in Tarakan, North Kalimantan, in 2019 led to significant infrastructure damage, financial losses, and prolonged power outages, highlighting the critical need for effective fire disaster preparedness. Despite the acknowledged high fire risk in industrial areas, including GEPPs, and the severe implications for critical national infrastructure, comprehensive, location-specific analyses of fire disaster preparedness are notably scarce in the existing literature, particularly for power generation facilities in rapidly developing regions like Jambi. While previous studies have assessed elements of fire safety management and preparedness, a holistic and integrated evaluation encompassing Building Safety Reliability Value (BSRV), fire management protocols, and worker preparedness within a single, critical GEPP context remains underexplored.

Given the severe potential consequences, an effective and efficient fire emergency response system is imperative for the Sei Gelam GEPP. Such a system must encompass early detection, rapid and appropriate response mechanisms (including evacuation and suppression procedures), and well-coordinated firefighting and rescue operations involving all relevant

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stakeholders. The success of these systems hinges not only on response speed but also on the accuracy of hazard identification, the adequacy of active and passive fire protection, the clarity of emergency procedures, and the preparedness and skills of personnel. Existing assessments often provide a fragmented view, either focusing solely on infrastructure compliance or individual worker readiness, without fully integrating these interdependent dimensions into a comprehensive management framework specific to complex industrial environments [4]. This gap is particularly urgent for facilities like the Sei Gelam GEPP, which underpin regional stability and economic activity, as any disruption could have cascading effects on the community and industry. The operational continuity and safety of such vital energy assets depend on a deeply integrated understanding of their unique fire risk profile and the readiness of all involved elements [5].

Unlike prior fragmented approaches, this research uniquely combines the assessment of Building Safety Reliability Value (BSRV) based on Pd-T-11-2005-C, detailed fire management protocols according to Indonesian Minister of Manpower Decree No. 186 of 1999 concerning Fire Suppression Units at Workplaces (Kepmenaker No. 186/1999), and an in-depth analysis of worker preparedness informed by the LIPI-UNESCO/ISDR 2006 framework. By thoroughly evaluating these interdependent aspects, this study aims to identify specific strengths and weaknesses within the Sei Gelam GEPP's current fire safety ecosystem. The findings will provide evidence-based, actionable recommendations not only for this specific facility but also offer a transferable methodology and valuable insights for enhancing fire disaster preparedness, minimizing losses, protecting assets, ensuring worker safety, and maintaining the continuity of vital electricity supply in similar critical energy infrastructures, thereby contributing significantly to health and safety practices in industrial disaster management.

2 Methodology

This study adopted a semi-qualitative research approach, integrating both quantitative and qualitative data collection and analysis methods to comprehensively assess fire disaster preparedness at the Sei Gelam GEPP. The on-site data collection from January to March 2025. The study location was the Sei Gelam GEPP in Jambi, situated at Lintas Pramuka No. 16, Kb. IX, Sungai Gelam District, Muaro Jambi Regency, Jambi 36361, Indonesia.

2.1 Data collection techniques

1. Field Observations
   Systematic recording of the physical condition, installation, and placement of fire emergency response system components, including active and passive fire protection systems (e.g., water suppression systems, portable fire extinguishers, building constructions, exit doors, emergency stairs). This aimed to evaluate the building's safety reliability against fire risks and operational activities in accordance with Pd-T-11-2005-C guidelines [6].
2. Interviews
   Structured interviews were conducted with four key personnel directly involved in fire management at the Sei Gelam GEPP. The interviews focused on assessing their understanding and adherence to the duties and requirements for fire role officers, firefighting teams, unit coordinators, and K3 (Occupational Health and Safety) experts, as stipulated by Kepmenaker No. 186 of 1999 [7].
3. Questionnaires
   Questionnaires were administered to 47 workers (derived from a population of 87 workers using the Slovin formula with a 10% margin of error) to measure their fire emergency preparedness levels. The questionnaire was structured based on the LIPI-UNESCO/ISDR (2006) [8] framework, covering knowledge, attitude, emergency response plans, early warning systems, and resource mobilization. A Guttman scale was used for knowledge questions, and a 1-5 Likert scale for attitude, emergency plans, early warning, and resource mobilization. Validity was ensured through expert review, and reliability was assessed using Cronbach's Alpha (acceptable if $\alpha \geq 0.6$).

2.2 Data Analysis

Data analysis involved both descriptive and inferential statistics to describe each research variable based on frequency distribution.

1. Building Safety Reliability Value (BSRV) Analysis
   Based on Pd-T-11-2005-C, BSRV components (Site Completeness, Evacuation Facilities, Active Fire Protection Systems, and Passive Fire Protection Systems) were rated as "Good" (B), "Sufficient" (C), or "Insufficient" (K) with equivalent scores of 100, 80, and 60, respectively. The overall BSRV was calculated as a weighted sum of these components.

$$\text{BSRV} = \sum_{i=1}^{n} (Wi \times Si) \tag{1}$$

2. Fire Management Analysis
   Interview data was analyzed using a checklist based on Kepmenaker No. 186 of 1999. Compliance was scored as 1 (compliant) or 0 (non-compliant), and the percentage of compliance was calculated as:

$$P = \frac{\text{total real score parameter}}{\text{maximum score parameter}} \times 100\% \tag{2}$$

3. Worker Preparedness Analysis: Questionnaire data was scored according to the LIPI-UNESCO/ISDR (2006) index. The index value for each parameter was calculated as:

$$\text{Index} = \frac{\text{total real score parameter}}{\text{maximum score parameter}} \times 100\% \tag{3}$$

   The overall preparedness level was categorized as "Very Prepared" (80-100), "Prepared" (65-79), "Almost Prepared" (55-64), "Less Prepared" (40-54), or "Not Prepared" (<40).

3 Results and discussion

3.1 Building safety reliability value (BSRV)

The overall BSRV at the Sei Gelam GEPP was assessed at 96.34%, falling into the "Good" category. This indicates a high level of compliance with fire safety standards in terms of building structure and facilities. The BSRV is derived from the summation of scores for all evaluated components: site completeness, evacuation facilities, active fire protection systems, and passive fire protection systems. The comprehensive results of this assessment are presented in Table 1.

Table 1. Recapitulation of BSRV scores

No	BSRV Parameter	Weight (%)	Score (%)
1	Site Completeness	25	25
2	Evacuation Facilities	25	25
3	Active Fire Protection Systems	24	23.67
4	Passive Fire Protection Systems	26	22.67
	Total		**96.34**

1. Site Completeness
This component achieved a perfect score of 100%. The facility boasts sufficient water tank capacity (700 m^3 against a minimum need of 4.35 m^3/day), well-maintained access roads (6m wide, hard surface), adequate building separation (101m to the nearest residential area), and accessible, regularly tested outdoor hydrants. These factors significantly enhance external firefighting access and prevent fire spread.
2. Evacuation Facilities
This component also scored 100%. The Sei Gelam GEPP provides five fire-resistant exit doors (2.5m high) leading to open areas, clearly marked with exit signs. Exit routes are constructed from fire-resistant concrete and brick (2-3 hours fire resistance) and are free from obstructions, with fire-resistant aluminum frames for doors and ventilation to prevent smoke propagation. The absence of a helicopter landing pad did not negatively impact the score as it is not a requirement for buildings under 60m in height.
3. Active Fire Protection Systems
This component received a score of 98.58% (calculated as 23.66/24 * 100%), placing it in the "Good" category.
   a. Detection and Alarm Systems
   Scored 100%. The facility is equipped with 187 smoke detectors, 74 heat detectors, and both manual and automatic alarms, all functioning optimally with easily accessible control panels.
   b. Siamese Connection
   Scored 100%. A well-marked and easily accessible Siamese connection on the west side of the building ensures external water supply for firefighting.
   c. Portable Fire Extinguishers (PFE)
   Scored 100%. There are 72 dry chemical powder PFEs and 30 CO_2 PFEs, regularly inspected and refilled, optimally placed according to NFPA 10 standards.
   d. Building Hydrants
   Scored 100%. Fourteen building hydrants (one in the lobby, thirteen in the engine hall) are well-maintained, fully equipped, and strategically placed.
   e. Sprinklers
   Scored 100%. Fifty-nine sprinklers are strategically located in both light and heavy fire risk areas, compliant with requirements.
   f. Deluge Fire Suppression System
   Scored 100%. Specific fire suppression agents (powder, CO_2, foam PFEs) are available in sensitive areas like the control room, generator room, and battery room, matching the potential hazards.
   g. Smoke Control and Detection
   Scored 100% for both, respectively. Smoke exhaust fans activate automatically upon smoke detection, and 187 smoke detectors ensure early warning.
   h. Smoke Exhaust
   Scored 80%, categorized as "Sufficient". This is an area for improvement as the existing ventilation system and selectively installed exhaust fans are insufficient in capacity.
   i. Fire Lift
   Scored 100% as it is not applicable for buildings under 25m.
   j. Emergency Lighting and Exit Signs
   Scored 100%. These systems are well-installed in emergency stairs and function automatically during power outages, with clear exit signs.
   k. Emergency Power
   Scored 100%. Battery-powered emergency electricity activates automatically during power failures.
   l. Operation Control Room
   Scored 100%. The control room is fully equipped with CCTV, sound systems, communication tools, PFEs, and alarm/electrical control panels, staffed 24/7.
4. Passive Fire Protection Systems
This component achieved a score of 87.19% (calculated as 22.67/26 * 100%), categorized as "Good".
   a. Fire Resistance of Building Structure
   Scored 100%. The concrete structure provides excellent fire resistance, meeting Type A construction requirements.
   b. Space Compartmentation
   Scored 100%. Effective use of fire-resistant walls and adequate access roads aids in containing fire spread.

c. Opening Protection
Scored 60%, categorized as "Insufficient". This is a critical weakness as the building lacks specifically designed openings for firefighter access, potentially hindering emergency operations and accelerating fire/smoke spread.

3.2 Fire management

The interviews revealed the general condition of fire management within the Sei Gelam GEPP. The recapitulation of the interview results regarding fire management can be seen in Table 2. Fire management at the Sei Gelam GEPP generally falls into the "Good" category across key roles, though specific areas require enhancement for full compliance and optimized readiness.

Table 2. Recapitulation of fire management interview results

No.	Fire Suppression Unit	Score	Category
1	Fire Role Officers	100	Good
2	Firefighting Teams	93	Good
3	Fire Control Unit Coordinator	86	Good

1. Fire Role Officer
Achieved 100% compliance. These officers effectively identify and report hazards, extinguish initial fires, guide evacuations, secure fire locations, and coordinate with relevant agencies, demonstrating a high level of training and understanding. Regular training (biannual) and participation in basic fire suppression courses contribute to this high score.
2. Firefighting Teams
Achieved 93% compliance. While proficient in most tasks, including hazard identification, equipment maintenance, initial fire suppression, and first aid, the team does not actively participate in drafting the fire emergency response plan book. This is attributed to relying on a general guideline from the Jambi Power Generation Business Unit (UBP). Direct involvement in plan development is crucial for enhancing team ownership and practical applicability.
3. Fire Control Unit Coordinator
Achieved 86% compliance. The coordinator effectively leads initial suppression efforts, develops work programs, and proposes budgets. However, a significant gap is the lack of "Ahli K3 Pratama" (Entry-Level OHS Expert) certification, which is vital for in-depth knowledge in fire inspection, hazard evaluation, and risk management.
4. Specialized Fire OHS Expert
Currently, the Sei Gelam GEPP employs general OHS experts but lacks specialized fire OHS experts. This poses a gap in developing and implementing comprehensive fire suppression programs, conducting in-depth risk analysis, and providing specialized personnel training.

3.3 Worker preparedness

The fire preparedness level of workers is categorized into five levels: very prepared, prepared, almost prepared, less prepared, and not prepared, derived from the questionnaire data of 47 respondents. This assessment utilized the LIPI-UNESCO/ISDR (2006) preparedness index scoring, incorporating five key indicators: knowledge, alert attitude, emergency response plan, early warning system, and resource mobilization. The combined index value for overall worker preparedness is 86, placing it in the 'Very Prepared' category. A comprehensive summary of these findings is presented in Table 3.

Table 3. Recapitulation of fire preparedness level questionnaire results

Parameter	Real Score	Max. Score	Index	Category
Knowledge	366	470	77.87	Prepared
Alert Attitude	1,699	2,115	80.33	Very Prepared
Emergency Response Plan	2,310	2,585	89.36	Very Prepared
Early Warning System	1,250	1,410	88.65	Very Prepared
Resource Mobilization	1,044	1,175	88.85	Very Prepared
Overall Preparedness Level	**6,669**	**7,755**	**86**	**Very Prepared**

1. Knowledge of Fire
The average index for knowledge is 77.87, categorized as "Prepared". While 63.83% of workers are "Very Prepared," a notable 14.89% are "Less Prepared". Specific weaknesses include understanding PFE types and functions (40% incorrect), fire classification (38% incorrect), and PFE usage steps (28% incorrect).
2. Fire Alert Attitude
The average index for attitude is 80.33, categorized as "Very Prepared". 51.06% of workers are "Very Prepared," with 36.17% "Prepared". However, there's a concerning sentiment where 17% disagree/26% strongly disagree that workers must be capable of suppression and rescue, and 26% disagree/26% strongly disagree with arbitrary PFE relocation. These indicate a need for a stronger sense of personal responsibility and adherence to safety protocols.
3. Emergency Response Plan
The average index for emergency response plans is 89.36, categorized as "Very Prepared". 78.72% of workers are "Very Prepared". A key weakness identified is that 13% disagree regarding the company's emergency communication system, suggesting some workers may not be fully aware or confident in using it.
4. Early Warning System
The average index for early warning systems is 88.65, categorized as "Very Prepared". 82.98% of workers are "Very Prepared". A minor concern is

that 13% disagree on knowing the location of water sources or fire extinguishing tools.

5. Resource Mobilization
The average index for resource mobilization is 88.85, categorized as "Very Prepared". 63.83% of workers are "Very Prepared". However, 6% disagree that they can perform first aid effectively.

3.4 Recommendations

1. Enhance Building Safety Reliability Value (BSRV)
   a. Implement a rigorous schedule for periodic inspection, maintenance, and repair of all fire safety system components, particularly focusing on components susceptible to wear and tear or those identified as "Insufficient" (e.g., opening protection in passive fire systems) [9]. This proactive approach is crucial to sustain the "Good" BSRV over time.
   b. Address the "Sufficient" rating by installing comprehensive, ceiling-mounted smoke exhaust fans that are integrated with the emergency power supply and automatic fire detection system [10]. This is critical for maintaining visibility and facilitating safe evacuation during fire incidents.
   c. Implement measures to protect building openings, especially for firefighter access, by installing fire-rated doors and windows where necessary to prevent rapid fire and smoke spread [11].
2. Strengthen Fire Management
   a. Maintain the high level of compliance by continuing regular bi-annual fire suppression training and ensuring continuous participation in technical fire suppression courses. Introduce dynamic, real-time fire risk maps integrated with sensor data to enable proactive identification and prevention of potential fires [11]. Foster combined training sessions with firefighting teams and medical personnel to enhance inter-team coordination. Implement user-friendly incident and near-miss reporting systems to identify trends and inform continuous improvement. Incorporate physical fitness programs into training to ensure officers are physically capable of demanding emergency tasks.
   b. Mandate active participation of firefighting teams in the development and regular updating of the fire emergency response plan book [12]. This direct involvement will foster ownership and ensure the plans are practical and effective, complementing the existing UBP Jambi guidelines. Conduct more frequent and integrated simulations and drills to test and refine these plans.
   c. The coordinator must obtain "Ahli K3 Pratama" certification to acquire comprehensive OHS knowledge, including legal aspects, risk management, and advanced inspection techniques. Additionally, provide leadership training emphasizing rapid decision-making, clear communication, and stress management under high-pressure scenarios [13]. Include training in contingency planning, complex suppression strategies, and coordination with external emergency services. Introduce training on advanced fire safety technologies such as drones for monitoring and advanced automated suppression systems.
   d. Consider recruiting or training a specialized fire expert to oversee comprehensive fire prevention programs, conduct in-depth risk analyses, and provide tailored training, bridging the current knowledge gap.
3. Improve Worker Preparedness
   a. Implement more focused and practical training for workers on PFE types and functions, fire classification, and detailed PFE usage steps to address identified knowledge gaps.
   b. Emphasize in training that all workers are expected to be capable of basic suppression and rescue efforts where safe, and strictly enforce rules regarding the proper placement of fire extinguishing equipment [14].
   c. Ensure all workers are thoroughly familiar with and proficient in using the company's emergency communication system to contact emergency teams or other employees during incidents.
   d. Increase hands-on training for first aid in fire-related injuries to boost worker confidence and capability [15].
   e. Conduct more complex and realistic fire simulations that incorporate scenarios such as limited visibility, injured victims, equipment failure, partial building evacuations, and responses to false alarms. These simulations should stress teamwork and inter-team coordination (e.g., internal firefighters, first aid, control room operators). Communication training should prioritize clarity, conciseness, and effectiveness under pressure.
   f. Develop more detailed operational recovery procedures (including equipment and system recovery priorities), public communication strategies, psychological support plans for workers post-incident, and identify alternative resource sources (e.g., temporary power supply).

4 Conclusions

This study concludes that the Sei Gelam GEPP demonstrates a commendable level of fire disaster preparedness. The Building Safety Reliability Value is categorized as "Good" (96.34%), reflecting robust structural and facility compliance. Fire management, encompassing fire role officers, firefighting teams, and unit coordinators, also shows a "Good" rating (100, 93, and 86 respectively), indicating effective training and organizational structure. Furthermore, worker preparedness is assessed as "Very Prepared" (index value of 86).

Despite these strengths, critical areas for improvement include enhancing smoke exhaust systems, mandating Ahli K3 Pratama certification and advanced leadership training for fire control unit coordinators, and implementing more complex, realistic fire simulations that foster robust inter-team coordination. Addressing these specific recommendations will further fortify Sei Gelam GEPP's fire emergency response capabilities, minimizing potential health impacts on personnel, safeguarding critical infrastructure, and ensuring the continuous and safe supply of electricity. This research serves as a valuable case study, providing insights for other vital energy infrastructures in developing their risk-based disaster preparedness framework.

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