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A Study on Health, Safety, Environment, and Ergonomics (HSEE) in Solar Power Plant

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ABSTRACT

Solar energy has rapidly developed as a renewable energy source, but the aspects of Health, Safety, Environment, and Ergonomics (HSEE) in their operations have remained a concern. This study analysed the risks faced by workers and the environment at the Pantai Baru solar power plant using a risk analysis approach based on primary data from worker questionnaires and secondary data from literature reviews and field observations. The findings showed that the health aspect included heat stress such as prolonged under direct sunlight and exposure to toxic materials, these materials include heavy metals such as cadmium (Cd) and lead (Pb), which are commonly used in photovoltaic (PV) technology to enhance efficiency but are known to be carcinogenic and hazardous even at low doses. The safety aspect covered electrical hazards, fire hazards, and falling risks, all of which were exacerbated by suboptimal working conditions. From an environmental perspective, solar power plants caused ecosystem damage, required large land areas, and faced challenges in recycling solar panels and batteries. Ergonomic risks were also identified, but the questionnaire results indicated that musculoskeletal injuries were not a significant issue for solar power plant workers. This study concluded that most HSEE sub-variables were relevant to the risks associated with solar power plants, except for musculoskeletal injuries. Therefore, implementing risk mitigation strategies, improving workplace design, and enforcing stricter environmental policies were necessary to ensure safe, efficient, and sustainable solar power plant operations.

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1. Introduction

Energy is a fundamental necessity in human life, and its consumption tends to increase in line with national development. According to the 2021 Electricity Supply Business Plan (RUPTL), Indonesia, classified as a developing country, was projected to experience an average annual electricity demand growth of 4.9%. To meet this demand, the government targeted a total power plant development of 40.575 MW, of which 20.923 MW was allocated for new and renewable energy (NRE).

Despite Indonesia's significant NRE potential estimated at 3686 GW by the Ministry of Energy and Mineral Resources (ESDM, 2023), the installed power capacity as of 2022 only reached 81.2 GW. In 2023, the renewable energy mix in the primary energy supply stood at just 13.1%, falling short of the 23% target set for 2025 in the National Energy Policy (KEN) [1] . To achieve net-zero emissions (NZE) by 2060, Indonesia will continue to promote renewable energy utilisation, reduce fossil fuel consumption, and transition to low-carbon energy sources [2].

An increase in the renewable energy mix has become a global priority to support decarbonization. One potential clean energy source is solar power, especially in countries with high solar radiation levels [3]. Indonesia has significant solar energy potential due to its location on the equator, with an average solar radiation intensity of 4.8 kWh/m² per day or approximately 1.752 kWh/m² per year [4]. The use of solar radiation can be optimised through the development of solar power plants. Solar power plants convert solar energy into electricity using environmentally friendly technologies. These systems offer several advantages over conventional fossil-based plants, including reduced fuel dependency, lower greenhouse gas (GHG) emissions, and minimal operational costs [5]. However, the implementation of solar power plants also presents challenges related to health, safety, environment, and ergonomics that need to be addressed [6].

HSEE is a structured management system designed to identify and control risks using standards-based approaches [7]. Additionally, the integration of ergonomic considerations into system design can improve the interaction between workers and their tasks, thereby enhancing productivity, safety, and job satisfaction [8]. Several studies have examined the HSEE aspects of solar power plants. An experiment conducted on PV panel combustion showed that hazardous gases such as sulfur dioxide (SO_2), hydrogen fluoride (HF), and hydrogen cyanide (HCN) can be emitted [9]. Furthermore, PV technology often uses heavy metals such as cadmium (Cd) and lead (Pb) to enhance efficiency, which are carcinogenic and hazardous even at low doses [10]. The operation of solar power plants can impact the surrounding environment, leading to water quality degradation and ecosystem damage [11]. Additionally, the development of solar power plants requires large land areas and GHG emissions at various stages, from production to operation [12].

Although research on the HSEE in solar power plants has been conducted, a gap remains in the comprehensive understanding of the variables that constitute the HSEE as a whole. Therefore, this study aimed to identify and further explain the HSEE variables in solar power systems, providing deeper insights into the factors influencing HSEE and supporting the development of safer and more efficient solar power plants.

2. Method

This study employed a qualitative research approach and was carried out at the Pantai Baru Solar Power Plant through direct observation from September 23 to 27, 2024. The data sources included both primary and secondary data. Primary data were obtained directly from key informants and respondents at the research site through interviews and questionnaires. These data were not available in pre-existing documents or files, but were collected firsthand. Meanwhile, secondary data consisted of supporting information gathered from literature and documents related to similar topics.

2.1. Research Sites

Pantai Baru Solar Power Plant is located in Ngentak, Poncosari, Srandakan, Bantul Regency, Yogyakarta. This location was selected because it is an important research site for renewable energy power plants. The Pantai Baru Solar Power Plant was built in 2010 on a 13 m × 15 m area above a fish farming pond. It was a hybrid power plant consisting of 140 solar panels, 40 batteries, and other components.

2.2. Data Collection Techniques

In this study, data collection was conducted using four main methods: literature review, observation, interviews, and questionnaire distribution. This multi-method approach aimed to obtain a comprehensive understanding of the Health, Safety, Environmental, and Ergonomic (HSEE) aspects in the operation of the Pantai Baru Solar Power Plant. The literature review examined various scientific articles and research reports focused on HSEE aspects of solar energy systems. These secondary data sources included publications, websites, books, journal articles, and internal records [13]. Direct observation was conducted on-site to assess working conditions and identify potential risks to workers. Interviews were carried out with field workers to gain deeper insights into the implementation and challenges of HSEE practices. Questionnaires were distributed to evaluate the relevance of variables related to HSEE. The questionnaire specifically assessed various factors, including heat stress from prolonged sun exposure, toxic substances such as heavy metals in PV components, electrical hazards, fire risks, fall hazards, and ecosystem damage. It also covered environmental issues such as land use and material recycling, as well as ergonomic risks such as manual handling, musculoskeletal injuries, and poor work posture.

2.3. Data Analysis Techniques

Data analysis was conducted using a qualitative descriptive approach to understand and evaluate the Health, Safety, Environment, and Ergonomics (HSEE) aspects of the Pantai Baru Solar Power Plant. The analytical techniques involved several key stages, including data processing, validation, and result interpretation. The questionnaire data, which used a Likert scale of 1–5, were analysed to assess the relevance of the HSEE subvariable based on the respondents' perceptions of the Pantai Baru Solar Power Plant. This scale was used to measure the extent to which the subvariable obtained from the literature review aligned with the field conditions. Validation was conducted by comparing the questionnaire results with other primary data, namely, direct observations and interviews with workers. The purpose of this validation was to ensure that the variables identified in the literature review accurately reflected the operational conditions and challenges at the Pantai Baru Solar Power Plant.

The data analysis results were then used to draw conclusions regarding the HSEE aspects of plant operations. The results were interpreted by comparing research findings with previous literature and evaluating the relevance and potential application of recommendations related to risk mitigation and the improvement of HSEE aspects at the Pantai Baru Solar Power Plant.

3. Results and Discussion

3.1. Questionnaire

The questionnaire was distributed to respondents who worked directly at the Pantai Baru Solar Power Plant. Table 1 presents the data from five respondents who assessed the HSEE subvariable. The questionnaire used a Likert scale ranging from 1 to 5, where a score of 1 indicated "highly irrelevant," and a score of 5 indicated "highly relevant." Variables with an average score below 2 were considered irrelevant, whereas variables with an average score above 2 were considered relevant for measuring the sub-variables of Health, Safety, Environment, and Ergonomics.

The research findings indicated that several subvariable indicators had high average scores, making them relevant for workers at the Pantai Baru Solar Power Plant. Electrical hazards caused by work equipment (average score: 3.0) and the large land area required for plant operations (average score: 3.2) were the primary concerns in terms of safety and environmental aspects. In addition, exposure to hazardous chemicals and the risk of falling during installation and maintenance (average score: 2.6) were considered relevant.

Table 1. Respondents' HSEE Variable Indicator

HSEE Variable Indicator	Respondents					Average
	1	2	**3**	**4**	**5**	
Workers are potentially experiencing heat stress in the workplace	2	2	4	1	2	2.2
Workers are potentially exposed to hazardous chemicals/materials used in the workplace	2	3	3	4	1	2.6
Workers are potentially at risk of electrical hazards caused by workplace equipment	5	2	4	3	1	3.0
Workers are potentially at risk of fire due to workplace equipment	2	2	4	1	1	2.0
Workers are potentially at risk of falling during installation, maintenance, and operational activities at the workplace	2	2	4	4	1	2.6
Solar Power Plants potentially damage the ecosystem in the work environment	2	2	4	1	1	2.0
Solar Power Plants potentially require large areas of land for their operations.	2	3	4	4	3	3.2
Solar Power Plants recycle the materials used	4	3	3	1	1	2.4
Workers are potentially at risk of musculoskeletal injuries while working	2	2	3	1	1	1.8
Workers are potentially at risk of poor posture while working	2	2	3	3	1	2.2
Workers are potentially at risk of manual handling injuries during installation, maintenance, and operational processes at work	2	2	3	2	1	2.0

On the other hand, the risk of musculoskeletal injuries had the lowest average score (1.8), indicating that ergonomics was less of a concern for workers. Overall, most indicators were deemed relevant for assessing HSEE aspects, with a primary focus on safety and environmental factors. Therefore, risk mitigation efforts should prioritise electrical hazards, falling risks, land use, and hazardous material management.

3.1. Discussion

Secondary data defining each variable of Health, Safety, Environment, and Ergonomics (HSEE) were obtained in this study. To strengthen the validity of the secondary data, primary data were collected through questionnaires distributed to workers at the Pantai Baru Solar Power Plant to confirm their relevance to actual working conditions. The questionnaire results obtained from the workers served as a crucial element in reinforcing the HSEE risk analysis. Workers' perceptions of health, safety, environmental, and ergonomic risks provided a realistic depiction of their daily working conditions. For example, although technical data indicated high environmental temperatures with potential for heat stress, the questionnaire results revealed that most workers rarely experienced symptoms of heat stress. This discrepancy indicates that adaptation mechanisms and mitigation efforts have already been implemented.

Additionally, perceptions of ergonomic risks reinforced findings related to musculoskeletal disorders (MSDs). The majority of respondents reported experiencing back pain or discomfort due to non-ergonomic working postures, particularly during the installation and maintenance of solar panels above the fish pond. This condition aligned with technical data showing working positions that required workers to bend over, reach overhead, or maintain balance on an unstable surface.

In the health variable, two sub-variables were identified: heat stress and toxic materials. Heat stress occurs due to exposure to environmental heat and physical activity, leading to increased metabolic heat production. When heat dissipation is insufficient, the body's core temperature rises, potentially leading to health issues such as heat exhaustion and heat stroke [13]. Workers at solar power plants face a high risk of heat stress because of prolonged exposure to high-intensity direct sunlight. However, the questionnaire results indicated that most workers rarely felt high ambient temperatures, despite technical data recording an increase in temperature.

Fig 1. shows the recorded temperature around the solar power plant at 09:16 a.m. on September 25, 2024, at 09:16 which reached 34.1°C. While this value does not represent long-term trends, it illustrates a snapshot of the high ambient temperature experienced during the observation period, which may contribute to heat stress risks when sustained over time. This discrepancy suggested adaptation to the working environment or mitigation efforts, such as the use of Personal Protective Equipment (PPE) and adjustments to work schedules to reduce excessive heat exposure.

Fig 1. The ambient temperature around Pantai Baru Solar Power Plant

Heavy metals such as cadmium (Cd) in CdTe and lead (Pb) are known carcinogens even at low concentrations [10]. If PV modules are not properly disposed of, these toxic metals can contaminate soil and water through leachate from damaged modules [14]. The risk of respiratory disorders and occupational diseases poses a threat to solar power plant workers because of exposure to these heavy metals. Therefore, proper waste management and control measures are crucial for minimising negative impacts on health and the environment.

Fig. 2 shows unused and unprocessed PV modules. The safety risks in solar power plant operations, under the safety variable, included three sub-variables: electrical hazards, fire hazards, and fall hazards. Electrical hazards could occur during installation, maintenance, and operation; therefore, the use of Personal Protective Equipment (PPE), such as helmets, gloves, and safety shoes, was necessary because electric current could still be present even when components were temporarily deactivated. At the Pantai Baru solar power plant, 40 battery units were used to store energy from the solar panels. One of the observed hazards was the explosion of a battery unit, which occurred in 2018. Based on field observations and information from plant personnel, the explosion was suspected to be caused by overcharging, which may have led to gas accumulation inside the battery due to inadequate ventilation.

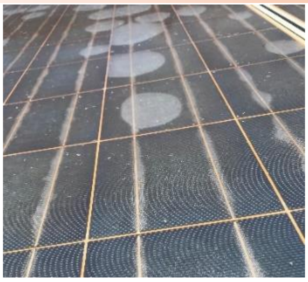

Fig 2. Damaged PV modules

The damaged battery, as recorded during the site visit, is shown in Fig.3. Although no direct measurement of overcharging was available, visual evidence and operational reports suggest that poor charging control and ventilation may have contributed to the incident. In addition, installation errors such as the use of cables that do not meet specifications can lead to electrical short circuits, resulting in current surges and excessive temperature increases in the battery. Physical damage to solar cells, including cracks, broken solder joints, and internal circuit short circuits, has also been identified as a potential cause of fire [15]

Fig 3. Exploded battery

Slip-and-fall accidents are the second most common type of nonfatal injury in the construction industry [6]. The installation of solar panels at the Pantai Baru solar power plant was considered to have a high risk of falling due to the unique structure of the facility, which was elevated 2 meters above the ground with a fishpond located 1 meter above it, as shown in Fig. 4. The position of the solar panels above the pond increased the risk of workers falling either into the pond or from a height. To minimise the risk of slip-and-fall accidents, the installation of safety equipment such as protective railings was recommended.

The environmental impacts of solar power plants include ecosystem degradation, land use, and material recycling. Floating solar power plants offer greater benefits than conventional land-based installations, such as the Pantai Baru solar power plant [11]. The main difference was the placement of the panels. The Pantai Baru plant was installed above a fishpond, whereas the floating solar power plants used buoyant systems directly on the water surface.

The cooling effect of water was observed in both the Pantai Baru and floating solar power plants, enhancing the solar panel efficiency. However, the cooling effect at installations above the fish ponds was optimal. Both types of installations could disrupt aquatic ecosystems by reducing water quality and dissolved oxygen levels, thereby limiting sunlight exposure needed by aquatic organisms. Additionally, the addition of solar power plants is required, posing a challenge if electricity demand increases. Another environmental impact was electronic waste generated from solar panels and batteries with short lifespans, which needed proper management and recycling to prevent environmental pollution.

Fig 4. Pantai Baru solar power plant building

The ergonomics variable in solar power plant operations included three sub-variables: manual handling risks, musculoskeletal disorders (MSDs), and working posture. The workers at the Pantai Baru solar power plant faced MSD risks due to non-ergonomic working positions, such as bending, reaching overhead, or maintaining balance on unstable surfaces. These conditions can lead to disorders affecting nerves, joints, and other body parts. The installation of solar panels and the use of heavy equipment also contributed to poor working posture, increasing the risk of lower back pain and musculoskeletal disorders [3]. These tasks include lifting and positioning solar panels at elevated heights, fastening bolts while crouching or twisting the body, and working for extended periods on narrow, unstable platforms above the water surface.

MSDs are among the most common types of occupational injuries and diseases worldwide [16]. The questionnaire results obtained from the workers at the Pantai Baru solar power plant reinforced these findings. Most respondents reported experiencing back pain or discomfort due to non-ergonomic working postures, especially during the installation and maintenance of solar panels above the fish pond, as illustrated in Fig. 5. This condition was consistent with the technical data, which indicated that workers frequently had to bend, reach overhead, or maintain balance on unstable surfaces. The consistency between the technical data and workers' perceptions highlighted the need for ergonomic improvements, such as training on proper working postures and providing assistive tools to reduce physical strain during work.

Fig 5 Pemeliharaan solar panel

4. Conclusion

The results reveal a variety of HSEE-related risks in the operation of solar power plants. Questionnaire data indicated that health issues, particularly heat stress, led to increased body temperature, dehydration, fatigue, and even heat stroke. Exposure to hazardous chemicals scored high in worker responses, with several plant components containing toxic substances if not handled correctly.

Safety concerns centred on electrical hazards, and the risk of falls during installation and maintenance also emerged as a critical issue. During operation, Pantai Baru relies on batteries for energy storage; overcharging these batteries, if combined with exposure to sparks, can result in serious incidents such as fires. Sub-variable analysis further demonstrated that health and safety aspects are closely interrelated and play a vital role in maintaining safe working conditions.

In addition, environmental and ergonomic risks were also observed to be interconnected. The unique design of the solar power plant built above fishponds at an elevated height of two meters created unstable working conditions. Workers often had to bend, reach overhead, or balance on narrow, slippery surfaces during installation and maintenance activities. These non-ergonomic postures were associated with increased complaints of musculoskeletal disorders (MSDs), particularly lower back pain, which were confirmed through questionnaire responses. This affected not only worker health but also reduced work efficiency and speed.

From these findings, it can be concluded that the four HSEE variables are closely related and collectively influence the operational performance of the solar power plant. Poor health and safety conditions can hinder timely maintenance and technical handling, while environmental and ergonomic risks reduce productivity and increase the likelihood of errors. Therefore, managing these HSEE aspects comprehensively is essential to ensure the safe, efficient, and sustainable operation of solar power plants.

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