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Enegy Resilience Assessment Model Based on Risk Matrix Analysis and Monte Carlo Simulatation for Large-Scale Solar Photovoltaic Plant

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Abstract

Energy resilience has emerged as one of the most critical components in ensuring the world's energy supply stability and security, particularly a large-scale solar (LSS) photovoltaic plant. However, there is a missing standard and proper approach for comprehensively assessing the resilience of any energy system for large-scale solar. The main objective of this paper is to develop an energy resilience assessment model and to analyze the assessment of the energy resilience for large-scale solar using risk matrix analysis and the Monte Carlo simulation method. At first, the types of risk to be considered in assessing the impact of a LSS photovoltaic (PV) plant in Malaysia were identified through an interview session with the operator of the plant, and then the risk probability and risk impact for each risk type was assessed by providing a score. Next, the energy resilience index was analysed by calculating the risk rating to indicate the resilience of the energy system is either sustainable, moderate, severe or critical. Then, the base model of the energy resilience was expanded to perform a Monte Carlo simulation for considering uncertainty in the input of the risk matrix. After comparing those two models, it is observed that the results for the overall risk rating for the solar farm are in the “Moderate” level when risk matrix analysis was performed deterministically, meanwhile “Severe” level when Monte Carlo simulation was performed. The proposed risk matrix analysis in this paper help the developer and operator of the LSS photovoltaic plant in making decisions and counter measures to improve the energy resilience of the solar PV plant.

Keywords: Large-scale Solar, Energy Resilience, Risk Matrix Analysis, Monte Carlo Simulation

Introduction

Climate change has placed uncertainty on energy systems through catastrophic occurrences driven mostly by climate-related hazards, which are predicted to rise in severity and frequency (Shandiz et al., 2020). Due to its significance in reducing the dangers associated with the unavoidable disruption of systems, the term "resilience" has become more common in the research literature and popular scientific literature (Hosseini et al., 2016). Energy resilience has become one of the most important components in assuring the world's energy supply stability and security, especially for the large-scale solar photovoltaic plant. Energy systems and supply energy are challenged by several disruptive events that threaten to interrupt the operations and performance of energy systems in today's global and increasingly dynamic and unpredictable environment (Schlör et al., 2018). Energy sector dangers and social and economic systems have a bidirectional relationship. Thus, the influence of natural catastrophes, technology, and societal disturbances on the energy sector, as well as the consequences of dangers and hazards imposed by the energy industry on the environment and human society, are factors impacting social and economic systems. Nowadays, climate change has worsened globally. Over the last two decades, the globe has seen over 350 natural disasters per year (Maheshwari & Ramakumar, 2020). Climate change refers to changes in usual and unusual weather conditions (precipitation, solar radiation, wind speed), which have an impact on the effectiveness of both renewable and fossil-based energy systems (Jasiūnas et al., 2021). Droughts, floods, hurricanes, typhoons, severe temperatures, landslides, dry mass movements, wildfires, volcanic activity, and earthquakes are examples of these phenomena which can destroy the energy infrastructure temporarily or permanently.

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In ensuring the energy system for a large-scale solar photovoltaic plant is reliable and has a regular supply of energy and contingency measures in place, the development of an energy resilience model is needed. Therefore, conducting an energy resilience assessment model for the power plant as proposed in this study is crucial. The assessment could assist the developer and system operator in making decisions following disruptions and disasters. The qualitative evaluation methodologies are based on assessing resilience characteristics such as preparation, absorption capacity, resourcefulness, robustness, adaptability, consequence mitigation capability, and recovery capacity (Raoufi et al., 2020). The study focuses on the investigation of energy resilience assessment for a large-scale solar, in Malaysia. The method used for this investigation is both quantitative and qualitative analysis. Thematic analysis is adopted for data collection meanwhile the risk analysis assessment is adopted for measuring the severity level. This study aims to develop an energy resilience assessment model for a large-scale solar PV plant using risk matrix analysis and Monte Carlo simulation.

Methodology

Flow chart

The overall research framework comprises seven components: literature review, data collection of energy resilience assessment, formulation of energy resilience framework, energy resilience modelling development, model evaluation, performance analysis and technical paper preparation as depicted in Figure 1.

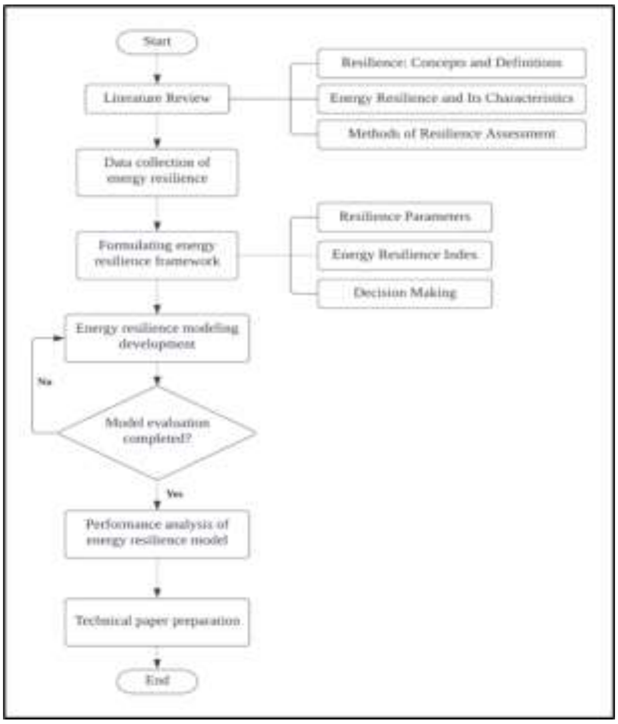

Figure 1: Flowchart for the proposed methodology for risk assessment analysis

Quantitative risk assessments have been used by scholars and practitioners to analyse the climate adaptation of solar power plants and other energy infrastructure [8]. Unfortunately, quantitative assessment methodologies are advocated for making short-term choices and accurately evaluating system resilience. Hence, in this paper, we develop a resilience assessment model which includes both qualitative and quantitative assessment methods for a large-scale solar in Malaysia. Generally, the development of the energy resilience model for the large-scale solar may be classified into two categories: qualitative and quantitative. They are namely thematic analysis, risk matrix analysis, and Monte Carlo analysis. Primarily, the study assesses the energy resilience index by calculating the risk rating of the solar farm to indicate the resilience of energy is either sustainable, moderate, severe, or critical.

Thematic Analysis

Thematic analysis is thought to be simple to understand. It detects significant issues and produces reflective insights from a large dataset by employing a flexible, yet well-structured that can adapt to various studies (Silva et al., 2021). In this research, thematic analysis is applied through self-administered observation and structured in-depth interviews. The type of risk for the risk matrix analysis is identified through literature review and interview sessions with the operator of the large-scale solar farm. The risks are classified into four types, natural risk, technical risk, human-made risk and others as shown in Table I.

Table 1
Data of power usage during testing

Natural risk	Technical risk	Human-made risk	Others
Flood	Transformer break down	Lawn mowing accidents	Birds' faeces on the solar panels
Fire	Inverter	New township development	The waterlogged area under panels
Heavy rainfall	M&E; Monitoring, CCTV, etc	Chemical use	
Erosion		Intruder	
Lightning			
Sediment			
Venomous animals; Snakes			
Pests; Rats			
Shadow; Trees			

Risk Matrix Analysis

The risk matrix analysis primarily determines whether there is a risk by analysing the risk identification indicators of the large-scale solar, assessing the potential impact of the risk and the probability of risk occurrence, and assessing the risk level according to predetermined standards. This approach is frequently used in engineering project management because it allows managers to simply and rapidly identify issues and conduct quantitative risk assessments (Hu et al., 2021). Risk probability can be expressed as the possibility of the occurrence of a specific event, which can be an effect or an outcome that may occur (Sreenath et al., 2020). It is divided into five groups in descending order of frequency as shown in Table II. If a recognized danger is likely to occur in the majority of cases, it falls into the “frequent” category. It is the highest concern since it occurs frequently. Similarly, risks that may emerge just a few times are classified as a "possible" category. Risks with the lowest rating occur seldom or under "exceptional" circumstances.

Risk severity can be defined as the intensity of the impact of a risk event. It can be classified as Catastrophic, Major, Moderate, Minor and Negligible as given in Table III. The rank for each severe risk is based on the percentage of the severity through discussion with the operator of the large-scale solar farm. The most severe risk has high priority and a percentage of 80% to 100% while the insignificant risk has the lowest priority with a percentage of 1% to 20%. In the LSS scenario, the severity of risk is assessed in terms of the factors and effects on the energy resilience at the solar farm. The impacts of severity are divided into three factors: cost, generation and safety. Then, the average of those three factors is taken as the risk severity index. If the hazard leads the system to shut down, damages the power plant, or includes death, it is termed as Catastrophic. The risk matrix is generally divided into four levels and marked with different colours. Red means critical, orange means severe, yellow means moderate and green means sustainable as depicted in Table 4. An increase in the likelihood and effects of an incident would increase risk. Risk analysis was performed to comprehend risk and the equation used to calculate risk rating is presented in equation (1).

Table 2
Types of risk probability

Name of probability	Descriptions	Probability ranking
Frequent	Expected to occur in most situations	5
Often	Probably occur at sometime	4
Possible	Might occur at sometime	3
Unlikely	Could occur at sometime	2
Exceptional	May occur in exceptional circumstances	1

$$Risk\ rating = Probability\ \times Impact \tag{1}$$

Monte Carlo Simulation

Monte Carlo simulation is utilised in a variety of engineering disciplines for a variety of reasons (Raychaudhuri, 2008). It is a sort of simulation that computes the outcomes through repeated random sampling and statistical analysis. In Monte Carlo simulation, the source for each of the input parameters is used to identify a statistical distribution. Thus, this simulation is implemented into this paper to consider the uncertainty of the input data which are risk probability and risk severity. Zeng et al. Zeng et al (2021) identified simulation approaches such as Monte Carlo simulations are employed in simulation-based methodologies to capture the unpredictable behaviours inherent in resilience quantifications such as in (Wei et al., 2020). Figure 2 shows the block diagram for the Monte Carlo Simulation in this study.

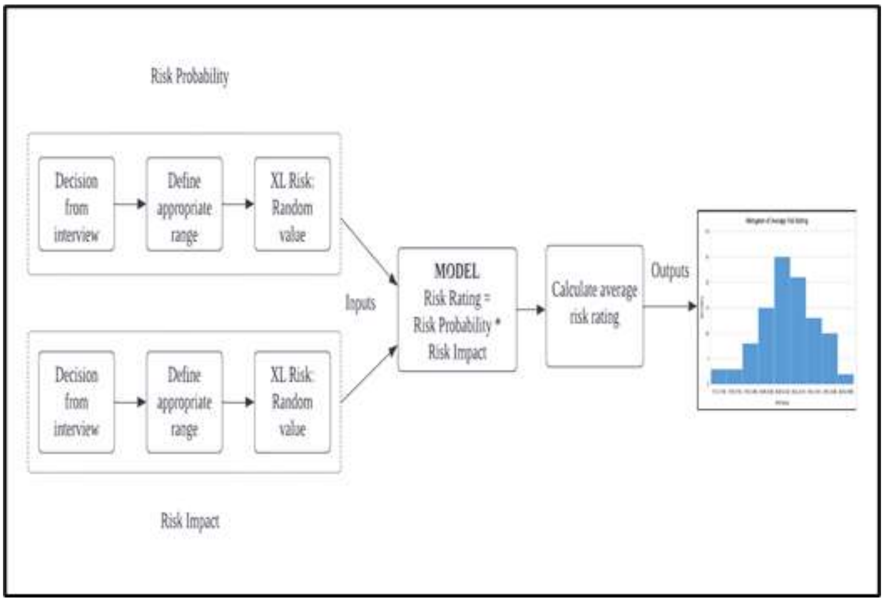

Figure 2: Block diagram of Monte Carlo Simulation

Results and Discussions

From the previous studies and interview sessions with the operator of the large-scale solar farm, all possible risks in the case study were identified for the energy resilience assessment. To rank and prioritize the risk of the large-scale solar PV, a risk matrix was used. Based on the risk probability and risk impact of each risk, a risk index is performed to get the risk rating for each risk as in Table V. Every risk has its level of risk rating.

Table 3

Risk severity and its description

Categories	Percentage severity (%)	Impact probability
Catastrophic	80 – 100	5
Major	60 – 80	4
Moderate	40 – 60	3
Minor	20 – 40	2
Negligible	1 – 20	1

Table 4
Risk index matrix (probability X impact)

Impact		**1**	**2**	**3**	**4**	**5**
Probability	**5**	Moderate 5	Severe 10	Severe 15	Critical 20	Critical 25
	4	Moderate 4	Moderate 8	Severe 12	Severe 16	Critical 20
	3	Sustainable 3	Moderate 6	Moderate 9	Severe 12	Critical 15
	2	Sustainable 2	Sustainable 4	Moderate 6	Severe 8	Severe 10
	1	Sustainable 1	Sustainable 2	Sustainable 3	Moderate 4	Severe 5

Table 5
Risk rating using risk matrix analysis

Type	Risk Name	Number	Risk Probability	Risk Impacts					Risk Rating
				Cost	Generation	Safety	Average	Round up	
Natural Risk	Flood	1	1	4	4	5	4.333	5	Severe
	Fire	2	2	5	2	5	4.000	4	Severe
	Heavy rainfall	3	5	5	4	1	3.333	4	Critical
	Erosion	4	3	5	1	3	3.000	3	Moderate
	Lightning	5	4	2	2	5	3.000	3	Severe
	Sediment	6	2	5	1	3	3.000	3	Moderate
	Venomous animals eg; Snakes	7	4	1	1	5	2.333	3	Severe
	Pest eg; Rats	8	4	1	1	5	2.333	3	Severe
	Shadow; Trees	9	3	1	1	1	1.000	1	Sustainable
Technical Risk	Transformer breakdown; HV 132kV	10	2	4	4	5	4.333	5	Severe
	Inverter; Solar panels; MV 33kV	11	3	3	3	3	3.000	3	Moderate
	Monitoring & Evaluation; CCTV, etc	12	5	2	1	1	1.333	2	Severe
Human-made risk	Lawn mowing accidents	13	2	1	1	1	1.000	1	Sustainable
	ECRL Routes	14	4	1	2	1	1.333	2	Moderate
	Chemical use	15	4	1	1	1	1.000	1	Moderate
	Intruder	16	2	5	1	1	2.333	3	Moderate
Others	Bird's faeces on the solar panels	17	5	1	1	1	1.000	1	Moderate
	Waterlogged area under panels	18	4	1	1	2	1.333	2	Moderate
Results:	**Average Risk (Round off)**		3.278					2.722	
			3					**3**	

Natural Risk

As shown in Table I, flood, fire, heavy rainfall, erosion, lightning and many more were natural risks indicated in the interview session with the operator at the solar farm. Since the severity of an extreme climatic event has the potential to disrupt plant operations, the operator stated even though they have not experienced a flood in the solar farm, if it happened, a flood is the biggest risk that will cause a huge impact on the power plant. Extreme precipitation caused the flood that wrecked the power plant (Dowling, 2013). Generally, the flood happened due to extreme rainfall and storm. Heavy rainfall and tropical storms can cause considerable flooding causing catastrophic damage to energy infrastructure and as a result, plant operation interruption. Not only that, but the consequences of heavy rainfall also affect erosion and sedimentation to occur. As depicted in Table IV, the risk rating for heavy rainfall is "critical" since both risk probability and risk impact is high.

Extreme weather events driven by climate change are predicted to become more frequent and severe (Cronin et al., 2018), inflicting harm to solar infrastructure. The closer a solar power plant is to a forest, the more likely it may be impacted by a forest fire. According to the operator, they had experienced a small fire that happened at the solar farm may be because the weather during that time was very hot. Lightning strikes may severely damage crucial electric components of energy systems, resulting in power outages and plant shutdowns (Dowling, 2013). The operator reported that unidentified lightning strikes destroyed the solar panels, but they didn't make any serious damage.

Technical Risk

From the discussion with the operators, it was found that technical risk is one of the most crucial issues of all. The operator informed that the transformer (HV 132kV) if break down would affect the whole system to shut down. The same goes for the inverter (MV 33kV), which would cause a 50 per cent operating effect.

Human-made Risk

Human-made acts were identified as one of the critical aspects that should never be disregarded during discussions with the operator on a variety of topics. The operator indicated that several panels had fractured as a result of grass mowing activity. Aside from that, the nearby construction from the township development may have an impact on the solar system structure's gravity due to the vibration and dust effect on the solar panels.

Others

Bird droppings on solar panels were always an underestimated and neglected nuisance. If bird droppings linger on the PV module for an extended time, solar operators face plenty of issues, including the possibility of severe production reductions. Meanwhile, the waterlogged area under the panels is caused by heavy rainfall. So, some countermeasures should have undergone to prevent waterlogging during the rainy season.

Risk Rating

Table 4 depicts the count of the risks in their level of severity. There are two risks under "Sustainable", eight risks under "Moderate", seven risks under "Severe", and one risk under "Critical" level. According to the assessment of the risk matrix analysis, as shown in Table V, the risk rating for all 18 types of risks that happened at the solar farm is determined. In this study, the average risk rating is taken as the result of the energy resilience assessment for the solar farm. It can conclude that the energy resilience assessment for the solar farm is "9" which is under the "Moderate" level.

Table 5

Count risk with their level of severity

Impact		**1**	**2**	**3**	**4**	**5**
Probability	**5**	1	1	0	1	0
	4	1	2	3	0	0
	3	1	0	2	0	0
	2	1	0	2	1	1
	1	0	0	0	0	1

Risk rating with Monte Carlo Simulation

Monte Carlo Simulation is performed to consider the uncertainty of the input. During the simulation, 100 iterations are performed until getting the results for risk probability, risk impact and average risk rating as shown in Figure 3, 4 and 5 below. According to the results of risk rating with Monte Carlo simulation, the mean of the graph is taken. Figure 3 depicts the histogram graph of risk probability with 100 iterations. In the graph, the mean for the risk probability is 1.01, meanwhile, Figure 4 shows a mean risk impact of 5.05. However, after combining both probability and impact, the mean for the average risk rating is 8.26 as shown in Figure 5. Thus, the score for risk rating is "8", with a "Severe" level as the mean for risk impact is higher than the mean for risk probability.

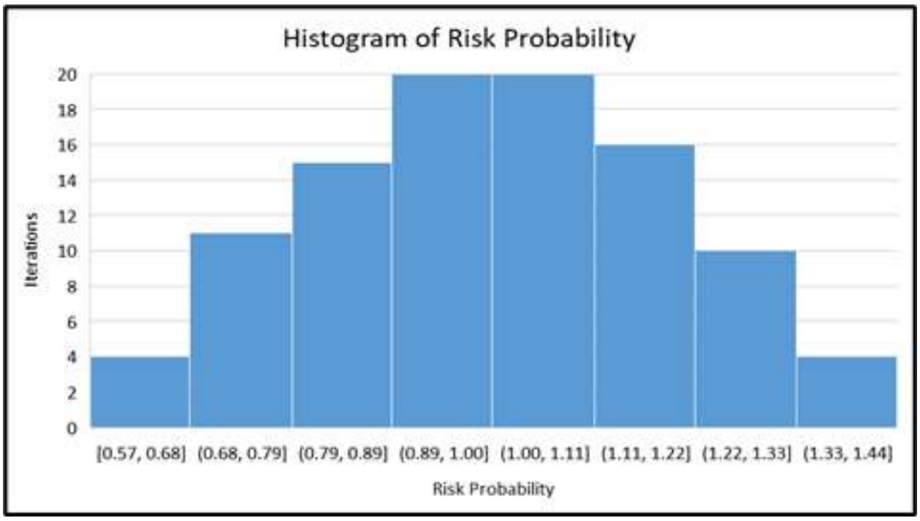

Figure 3: Histogram graph of risk probability

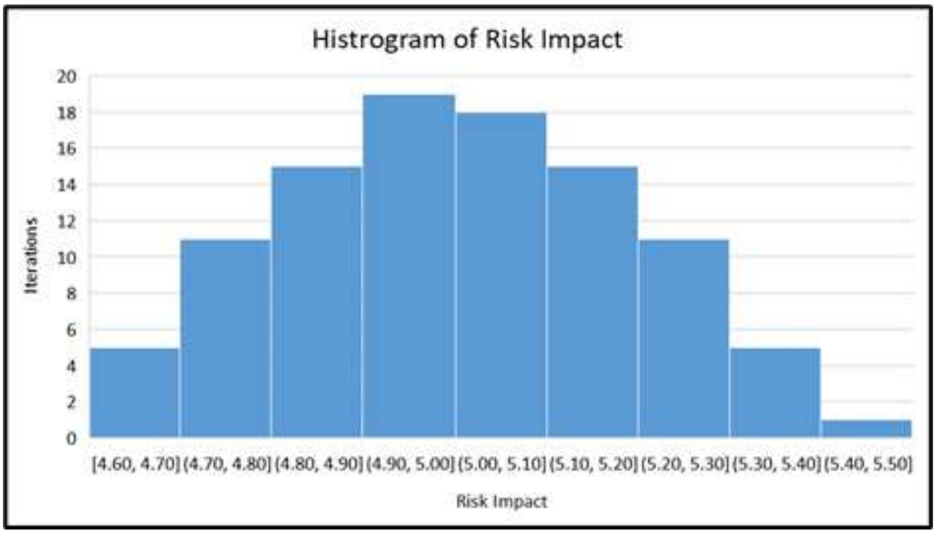

Figure 4: Histogram graph of risk impact

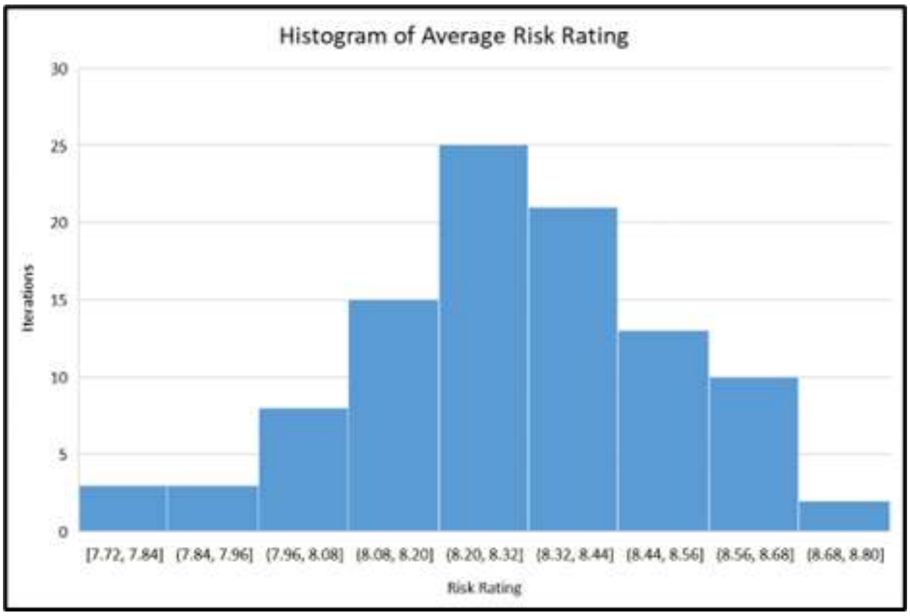

Figure 5: Histogram graph of average risk rating

Conclusion

Energy resilience involves enhancing the ability of energy infrastructure to withstand and adapt to both natural and the impacts of climate change. Resilience assessment is a vital tool for identifying and addressing the risks and vulnerabilities of solar PV power plants. This paper proposes a new approach for assessing the energy resilience of a large-scale solar PV plant based on risk matrix analysis and Monte Carlo Simulation method for analysing the effect of risk and uncertainty in prediction. The thematic analysis approach is assigned through the discussion with the operator of a large-scale solar farm in Malaysia for the data collection, types of risk at the solar farm, risk probability and risk impact. Then, the energy resilience modelling development is modelled based on risk matrix analysis and Monte Carlo simulation. The simulation results show that the vulnerability of the solar farm reaches the most when heavy rainfall risks occur. It was observed that the overall risk rating for the solar farm is in the "Moderate" level with a score of "9" when the risk matrix analysis approach is used, meanwhile "Severe" level with a score of "8" when Monte Carlo simulation is performed. The energy resilience assessment can be used by the developer and operator of the plant to plan for measures to improve the operation of the plant, recovering the plant from fault and protecting the infrastructure from any threats.

Since the solar farm sector is continually expanding, more research is needed to investigate this issue more thoroughly. Future work will favour research on the risk assessment with targeted risk rating after the implementation of the risk control strategy to preserve the energy of the large-scale solar PV, to include vulnerability factors in the energy resilience model and measures to reducing the risk impact to the power plant.

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