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Comparative Reliability Assessment of Solar Photovoltaic and Wind Energy Systems Using Failure Mode and Effects Analysis (FMEA)

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Abstract

This study presents a comparative reliability and risk assessment of solar photovoltaic (PV) and wind energy systems using Failure Mode and Effects Analysis (FMEA). With the rapid expansion of renewable energy infrastructure, understanding system-specific failure behavior has become essential for ensuring operational stability and long-term performance. The analysis identifies critical failure modes across key subsystems, including PV modules, inverters, turbine blades, gearboxes, and generators. Each failure mode is evaluated using Severity, Occurrence, and Detection parameters to compute the Risk Priority Number (RPN). The study further examines the influence of environmental and operational conditions such as temperature variation, dust accumulation, and wind variability on system reliability. The results demonstrate distinct risk profiles for the two technologies. Solar PV systems exhibit predominantly environment-driven degradation, resulting in distributed and manageable risks. In contrast, wind energy systems show higher criticality due to mechanical complexity and continuous dynamic loading, leading to more concentrated and severe failure modes. These findings emphasize the need for differentiated maintenance strategies, including preventive and condition-based approaches tailored to system characteristics. The proposed comparative framework provides practical insights for reliability assessment, maintenance planning, and decision-making in renewable energy system deployment.

Keywords: Solar Photovoltaic Systems; Wind Energy Systems; Reliability Analysis; Renewable Energy Systems; Failure Mode Analysis; Predictive Maintenance; FMEA; Risk Priority Number (RPN).

1. Introduction

The global transition toward renewable energy systems has intensified in response to increasing environmental concerns and the demand for sustainable power generation. Among the available technologies, solar photovoltaic (PV) and wind energy systems have emerged as dominant contributors due to their scalability, technological maturity, and economic viability. Despite their widespread adoption, ensuring system reliability and minimizing operational risks remain critical challenges for long-term performance and efficiency.

Solar PV systems are primarily influenced by environmental conditions such as dust accumulation, temperature fluctuations, and shading effects, which lead to gradual performance degradation. In contrast, wind energy systems involve complex electromechanical components, including blades, gearboxes, and generators, making them more susceptible to mechanical wear, dynamic loading, and abrupt failures. These fundamental differences result in distinct failure behaviors and risk distributions, highlighting the need for a structured comparative assessment.

Failure Mode and Effects Analysis (FMEA) is a systematic methodology widely used to identify potential failure modes, evaluate their impact, and prioritize risks based on severity, occurrence, and detectability. Although FMEA has been extensively applied across engineering systems, its application in comparative evaluation of renewable energy technologies remains limited. Existing studies predominantly focus on individual system analysis rather than offering an integrated perspective on multiple renewable technologies.

Recent research has highlighted the importance of linking reliability assessment with practical implementation and system-level analysis frameworks in renewable energy systems [6], [7]. However, there is a lack of comprehensive studies that explicitly compare the failure characteristics and risk profiles of solar and wind energy systems within a unified analytical framework.

This study addresses this gap by applying FMEA to both solar PV and wind energy systems to systematically identify failure modes, evaluate risk levels, and compare their operational reliability. The objective is to provide a structured basis for improving maintenance strategies, optimizing system performance, and supporting informed decision-making in renewable energy deployment.

2. Literature Review

Risk assessment and reliability analysis have become increasingly important in renewable energy systems due to their growing role in global energy infrastructure. Solar photovoltaic (PV) systems and wind energy systems, while environmentally sustainable, are subject to distinct operational and environmental challenges that affect their long-term performance and reliability.

In solar PV systems, previous studies have identified factors such as panel degradation, dust accumulation, temperature variation, and inverter failures as major contributors to efficiency loss and system downtime [1]. Environmental exposure plays a dominant role in influencing the performance of PV systems, often resulting in gradual degradation rather than sudden failure.

In contrast, wind energy systems are characterized by complex electromechanical structures involving components such as turbine blades, gearboxes, generators, and control systems. Research indicates that mechanical failures, particularly in gearboxes and blades, are among the most critical risks affecting wind turbine reliability and maintenance costs [2]. These failures often lead to higher downtime and require more intensive maintenance strategies compared to solar systems.

Various risk assessment methodologies have been applied in engineering systems, including Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Reliability Block Diagrams (RBD). Among these, FMEA is widely preferred due to its systematic approach in identifying failure modes and prioritizing risks based on Severity, Occurrence, and Detectability parameters [3]. Its simplicity and adaptability make it suitable for both qualitative and quantitative risk evaluation.

Several studies have applied FMEA in renewable energy systems to improve maintenance planning and reliability performance. However, most of these studies focus on individual systems rather than offering a comparative analysis between solar and wind technologies [4]. This limits the ability to understand relative risk profiles and prioritize system improvements across different renewable energy options.

Recent research and practical implementations have also highlighted the importance of integrating risk assessment with real-world applications and decentralized renewable energy systems [7]. Additionally, broader system-level analyses emphasize the need for structured frameworks that connect reliability assessment with operational and policy-level considerations [6].

Despite these developments, there remains a lack of comprehensive comparative studies that evaluate both solar and wind energy systems using a unified methodological framework. This study addresses this gap by applying FMEA to both systems and providing a structured comparison of their failure modes, risk levels, and mitigation strategies.

3. Methodology

3.1. System Description

The study focuses on two major renewable energy systems:

- Solar Photovoltaic (PV) Systems
- Wind Energy Systems

Each system is analyzed at the subsystem level to identify critical components that significantly influence overall reliability and performance. For solar PV systems, key components include PV modules, inverters, and mounting structures. For wind energy systems, the analysis considers turbine blades, gearboxes, generators, and control systems.

3.2. Risk Identification

The first stage of the methodology involves identifying potential failure modes associated with each system based on operational characteristics and existing literature.

Solar PV System Failure Modes:

- Panel degradation
- Dust accumulation
- Inverter failure
- Temperature effects

Wind Energy System Failure Modes:

- Gearbox failure
- Blade damage
- Generator faults
- Wind variability

These failure modes are selected based on their frequency of occurrence and impact on system performance.

3.3. Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is applied as the primary risk assessment tool. This method enables systematic identification, evaluation, and prioritization of potential failures within a system.

Each identified failure mode is evaluated using three parameters:

- **Severity (S):** Impact of the failure on system performance
- **Occurrence (O):** Likelihood of the failure occurring
- **Detection (D):** Ability to detect the failure before it occurs

The Risk Priority Number (RPN) is calculated using:

$$RPN = S \times O \times D$$

Higher RPN values indicate higher risk and require priority attention.

3.4. FMEA Evaluation Table

The calculated RPN values for each failure mode are presented in Table 1.

Table 1: *FMEA Evaluation of Solar and Wind Energy Systems*

System	Failure Mode	S	O	D	RPN
Solar	Panel degradation	7	6	5	210
Solar	Dust accumulation	6	7	5	210
Solar	Inverter failure	8	5	4	160
Solar	Temperature effects	6	6	5	180
Wind	Gearbox failure	9	6	4	216
Wind	Blade damage	8	5	5	200
Wind	Generator faults	7	5	4	140
Wind	Wind variability	6	7	6	252

3.5. System Representation

To visually represent the components and operational structure of the systems, schematic diagrams are included.

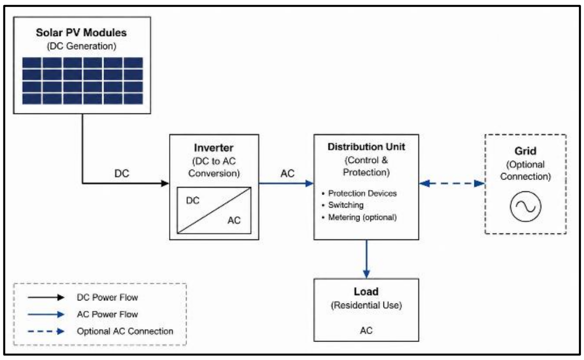

Figure 1: *Block Schematic Representation of Solar PV System Components*

The block schematic of the solar photovoltaic (PV) system represents the flow of energy from generation to utilization. Solar PV modules convert incident solar radiation into direct current (DC) electricity, which is then supplied to an inverter for conversion into alternating current (AC). The AC output is regulated and managed through a distribution unit that provides protection, switching, and control functions. The conditioned electrical power is then delivered to the load for end-use applications, such as residential consumption. In grid-connected configurations, excess power can be exported to the utility grid, or supplementary power can be drawn when required. This structured representation highlights the key functional stages of power conversion and distribution within a solar PV system.

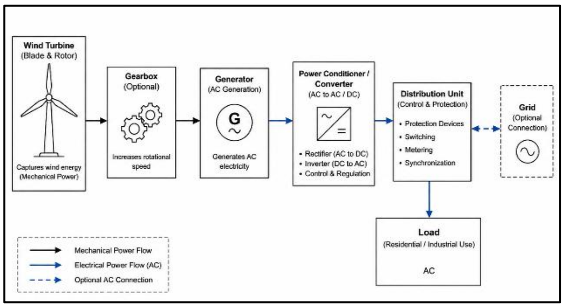

Figure 2: *Block Schematic Representation of Wind Energy System Components*

The block schematic of the wind energy conversion system illustrates the transformation of wind energy into usable electrical power. Wind turbines capture kinetic energy through rotor blades, which is transmitted via the hub and rotor shaft to the gearbox, where rotational speed is increased. The generator then converts this mechanical energy into electrical energy, typically in the form of variable-frequency AC. This output is conditioned using power electronics to ensure stable voltage and frequency suitable for utilization. The processed power is passed through a distribution unit for control and protection before being supplied to the load or integrated with the grid. Additional subsystems such as the nacelle, yaw system, and control system ensure proper alignment, monitoring, and efficient operation of the turbine.

3.6. Analytical Approach

The methodology follows a structured sequence:

- Identification of system components
- Determination of failure modes
- Assignment of Severity, Occurrence, and Detection values
- Calculation of Risk Priority Numbers
- Comparative analysis of solar and wind system risks

This approach enables a clear comparison of risk levels between the two systems and helps in identifying high-priority failure modes.

3.7. Scope and Assumptions

The study is based on generalized operating conditions and typical system configurations. The assigned values for Severity, Occurrence, and Detection are based on standard engineering judgment and literature-supported ranges. While the analysis provides a comparative understanding of risks, actual values may vary depending on site-specific conditions and operational environments.

4. Results and Discussion

The FMEA-based evaluation provides a comparative understanding of risk distribution across solar photovoltaic (PV) and wind energy systems. The calculated Risk Priority Number (RPN) values indicate that both systems are subject to distinct types of operational risks influenced by their design and working conditions.

In solar PV systems, the dominant risks are associated with environmental factors such as dust accumulation, panel degradation, and temperature effects. These factors tend to cause gradual performance deterioration rather than sudden system failure. The relatively moderate RPN values observed for solar components suggest that while failures are frequent, they are generally predictable and can be mitigated through regular maintenance practices such as cleaning, monitoring, and thermal management.

In contrast, wind energy systems exhibit higher RPN values, particularly in components such as gearboxes and generators. These components are subjected to continuous mechanical stress, dynamic loading, and wear, increasing the likelihood of critical failures. The presence of high RPN values in wind systems highlights the importance of mechanical reliability and the need for advanced maintenance strategies such as condition monitoring and predictive diagnostics.

A key observation from the analysis is the difference in failure behavior between the two systems. Solar PV systems are predominantly affected by external environmental conditions, leading to distributed and manageable risks. On the other hand, wind energy systems involve complex mechanical interactions, resulting in concentrated and potentially severe failure modes.

The comparative results indicate that solar PV systems offer higher operational stability and lower maintenance complexity, whereas wind energy systems require more rigorous maintenance planning and reliability management. However, wind systems may deliver higher energy output under favorable conditions, which justifies the need for improved risk mitigation strategies rather than system avoidance.

Overall, the findings emphasize that while both renewable energy systems are viable, their risk profiles differ significantly. Effective system design and maintenance strategies must therefore be tailored according to the specific failure characteristics of each technology to ensure long-term reliability and performance.

5. Conclusions

This study presented a comparative risk assessment of solar photovoltaic and wind energy systems using the Failure Mode and Effects Analysis (FMEA) approach. The analysis demonstrated that while both systems are essential components of the renewable energy transition, they exhibit fundamentally different risk characteristics.

Solar PV systems are primarily influenced by environmental factors, leading to gradual and predictable performance degradation. In contrast, wind energy systems are more susceptible to mechanical failures arising from complex moving components and dynamic operating conditions. As a result, wind systems require more advanced maintenance strategies and continuous monitoring to ensure reliable operation.

The findings highlight that system reliability is not solely dependent on technology type, but also on the nature of failure modes and their management. Solar systems offer operational simplicity and lower maintenance demands, whereas wind systems, despite higher risk levels, provide significant energy generation potential when supported by effective risk mitigation measures.

Overall, this study provides a structured framework for understanding and comparing the reliability of renewable energy systems. The insights can support engineers and decision-makers in selecting appropriate technologies, optimizing maintenance practices, and improving system performance in real-world applications.

Future work may focus on incorporating real-time operational data, advanced reliability models, and hybrid system analysis to further enhance the accuracy and applicability of risk assessment in renewable energy systems.

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