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RELIABILITY EVALUATION OF A HYBRID RENEWABLE ENERGY SYSTEM USING FAULT TREE ANALYSIS APPROACH

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ABSTRACT

Most rural communities in Nigeria still face inadequate power supply, while others await connection to the national grid due to their remote locations. To meet the energy requirements in these areas, the adoption of renewable energy sources has become crucial for society and the nation at large. Renewable energy resources are largely attractive because of their availability, environmentally friendly nature, and cost-effectiveness through continuous supply. However, due to their intermittent availability, hybrid renewable energy systems are employed to mitigate the drawback caused by their intermittency. In this study, the reliability of a complex hybrid renewable energy system involving five subsystems components is evaluated. The minimal cut-sets of the complex system were first determined, followed by the construction of the fault tree diagram. The failure variables associated with the parameters of each component were assumed to follow Weibull failure laws. The system's reliability was assessed for various arbitrary parameter values, such as failure rate (λ), shape parameter (β), and operating time (t) of the components. The results show that for λ = 0.01, the system reliability ranges from 0.97474 to 0.84816 for β values from 0.1 to 0.2, and t values from 10 to 20. For λ = 0.02, reliability ranges from 0.96671 to 0.57295 over the same parameter ranges. For $\lambda = 0.03$, the reliability varies from 0.95568 to 0.34419; for $\lambda = 0.04$, from 0.94058 to 0.19465; and for $\lambda = 0.05$, from 0.92004 to 0.10677, with β values between 0.1 and 0.2 and t between 10 and 20. The dynamics of these reliability indices are presented both graphically and numerically, based on arbitrary values of the system components' parameters.

KEYWORDS

Reliability; Weibull failure law; Failure rate; Shape parameter; Fault-tree; Minimal cut –sets.

1. INTRODUCTION

Reliability assessment of a system is a very important aspect of reliability engineering, as any modification or alteration to system component design may be costly and time consuming if still functional. In recent years, reliability assessment has gained tremendous attention from reliability engineering, as it provides the statistical rigor to model system. The urgency in energy decarbonization and the exponential increase in population, coupled with the industrial revolution, is causing Nigeria to face a very high energy demand, similar to many other developing countries around the globe (Ang et al., 2022). In most rural communities in Nigeria, many inhabitants still grapple with a lack of electricity supply due to economic and environmental constraints, such as highly hilly terrain in many rural areas, which makes grid extension economically unviable, among other issues (Muh et al., 2018). To realize the United Nations (UN) Sustainable Development Goal 7 (SDG 7) and promote socio-economic development, a more pragmatic, sustainable and uninterrupted electricity supply is crucial (Muh et al., 2018). In order to meet this energy demand, utilizing alternative, affordable, and clean energy sources has become necessary, occasioned by rising fossil fuel prices, environmental pollution, and the uncertain nature of fossil fuel (Okakwu et al., 2020; Okakwu et al., 2022; Okakwu et al., 2023(a); Okakwu et al., 2023(b); Okakwu et al., 2021). Renewable energy resources are highly promising alternatives to achieve the much anticipated energy transitioning towards a more sustainable and carbon-neutral economy due to their abundant availability and environmentally friendly properties. This urgent need to decarbonize the energy sector and mitigate climate change has positioned renewable energy system in the forefront of global energy decarbonization. Renewable energy sources depends largely on natural resources like solar and wind energy being the most popular among renewable energy resources, depending on the location of study (Raad and Nabeel, 2024; Al-Jabari et al., 2022). Employing hybrid renewable energy system has become necessary to mitigate the drawbacks intermittent nature of renewable energy resources (Hassan et al., 2023). Hybrid renewable energy systems has demonstrated significant contributions to electricity production worldwide. Unexpected system failure, which will lead to system downtime, has become a major stakeholders and investors issues. Hence, hybrid renewable energy system is important for reliable electricity supply. Reliability of a system is the ability of a system to function accurately under specified conditions for a period of time (Okakwu et al., 2019). Reliability is often express as the probability that a component will perform its needed function within a given period of time (t_0, t). In recent years, system designers and planners have explored various ways of interconnecting system components, including series, parallel, series-parallel, parallel-series, and mixed configurations. This means that assessing the system's reliability is necessary to understand how different configurations influence overall performance. It has been observed that the reliability of series components is generally lower than that of the most unreliable component, whereas the reverse is true for components connected in parallel (Sun et al., 2018). There are quite a number of literature that has investigated system reliability issues.

In (Ehiagwina et al., 2022), the review of FTA and its modification was studied. It was established from the results obtained that there are several areas of applications of FTA. The reliability of Egyptian grid network was evaluated using FTA by (Agwa et al., 2019). SAPHIRE-8 software was used for performing the FTA. The component parameters of the grid system is determined based on the technical impact on the grid system. The authors of (Song et al., 2014) locate the weak part of a system by using Monte Carlo simulation layered model, which prioritizes load. The method was applied to a smart grid network. Reliability evaluation of a power distribution network was assessed using FTA in (Adelabu et al., 2019). Reliability, availability and maintainability analysis of an on-grid PV system based on exponential distribution was investigated by (Sayed et al., 2019). Inverter thermal characteristics with FTA on PV system was investigated by (Li et al., 2021). Block diagram reliability techniques combined with exponential probability distribution model was used to analyze the reliability, availability and condition monitoring (RACM) of a photovoltaic PV system (Sarita et al., 2023). The subsystems components are arranged based on components contributions to overall system availability. The novelty in the RACM technique is its ability to monitor system performance frequntly. (Boryczko et al., 2022) investigated reliability assessment of water plant supply system using FTA. Reliability evaluation of a large-scale photovoltaic PV system using FTA was thoroughly investigated by (Sonawane et al., 2023). Reliability based assessment of hybrid solar/wind network was investigated by (Eryilmaz et al., 2021). (Kang et al., 2018) did offshore wind turbine reliability study using FTA approach. Locating the critical component of a wind turbine via FTA technique was done by (Ali et al., 2023). Reliability assessment of the effect of $k-out-of-n$ component of a photovoltaic PV system was investigated by (Mailhulla et al., 2021(a); Mailhulla et al., 2021(b)). The impact of component configuration on reliability system study for a large scale PV systems was investigated by (Baschel et al., 2018). Evaluating the reliability of a PV system by considering inverter thermal characteristics using FTA was studied by (Li et al., 2021). Long term reliability based performance of a hybrid system of solar and wind power system by considering the reliability value of the renewable energy source components was investigated by (Eryilmaz et al., 2021). In (Mutar et al., 2023), evaluation of reliability of complex safety-critical system considering exponential failure laws using matrices based minimal paths was studied.

With the aforementioned discussion, this research focuses on the reliability evaluation of a complex renewable energy system that follows the Weibull failure laws using the Fault tree approach. The model expression for reliability is obtained by considering identical components with arbitrarily values for the Weibull failure laws parameters. The fault tree model is an intuitive reliability approach that adequately covers component interaction and faults relationships between subsystems. It has the unique advantage of fast modelling because of it deterministic ability to link fault event through logic gates. Fault tree helps to analyze qualitatively by obtaining the minimum cut set and quantitatively by obtaining the system top-event respectively. Among the few existing reliability evaluation methods, fault tree analysis is arguably mentioned as one of the most useful techniques for reliability modelling of complex system.

The remaining part of this paper is sectioned as follows: Section 2 presents the methodology based on conceptual background and mathematical formulations of the approach used in this study. The results obtained are presented and discussed in section 3 while the study is concluded in section 4

2. MATERIALS AND METHODS

2.1. System Description

The system block diagram considered is a non-series-parallel system consisting of Solar PV, Wind turbine, battery, and inverter components, as shown in Fig.1. The PV panel or module converts solar energy into DC power. The wind turbine also converts wind energy into DC power. The battery system is used as a storage device in case of failure of the hybrid system (solar PV and wind turbine). The inverter system is employed to convert DC to AC power. The solar PV system is generally designed to operate for between 20 and 25 years. Furthermore, due to their exposure to the atmosphere, PV systems are often subjected to severe environmental challenges such as humidity, temperature variations, rain, dust, and others; hence, the need for a hybrid system, as shown in Fig.1.

2.2. The fault-tree method

The fault-tree approach is one of the most suitable methods for reliability assessment of a complex system due to its intuitive nature (Boolean logic). It is a graphical representation and analysis of critical occurrences that lead to a specific event, called the top event, P(T). The top event P(T) is an undesirable event, such as failure. The fault tree method is a deductive process that identifies the causes leading to system failure. A typical fault tree contains a top event, resultant events, AND/OR gates, and basic events, as depicted in Table 1.

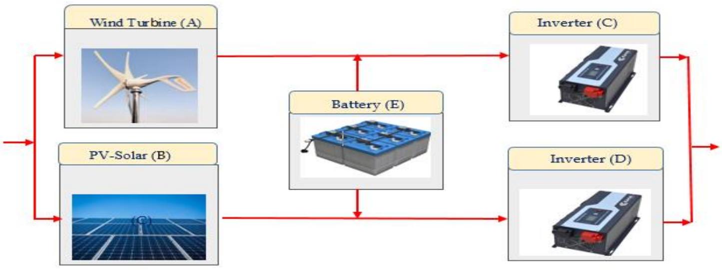
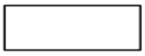
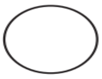


Fig. 1. Hybrid System Block Diagram

Table 1. Fault-Tree Symbol (Boryczko et al., 2022; Sonawane et al., 2023)

Name	Symbol	Meaning
AND gate		A logic gate where an output event occurs only when all the input events have occurred. In Boolean algebra, it is ∩ (intersection).
OR gate		A logic gate where an output event occurs if all at least one of the input events has occurred. In Boolean algebra, it is ∪ (union)
Resultant Event		A fault event resulting from the logical combination of other fault events and usually an output to a logic gate
Basic Event		An independent elementary event representing a basic fault on a component. The analysis ends with a basic event (there are no events below a basic event)

From Fig.1, a minimal cut-set of the system block diagram in Fig.1 is as follows:

$$C_{min} = \begin{cases} \{A:B\} \\ \{C:D\} \\ \{A:E:D\} \\ \{B:C:E\} \end{cases} \quad (1)$$

where $C_1 = \{A:B\}$, $C_2 = \{C:D\}$, $C_3 = \{A:E:D\}$ and $C_4 = \{B:C:E\}$

Equation (1) can also be written as follows:

$$C_{min} = \{A:B\}\ OR\ \{C:D\}\ OR\ \{A:E:D\}\ OR\ \{B:C:E\} \quad (2)$$

Converting the minimal cut-sets of Equ. 2 into a fault tree diagram, is shown in Fig. 2.

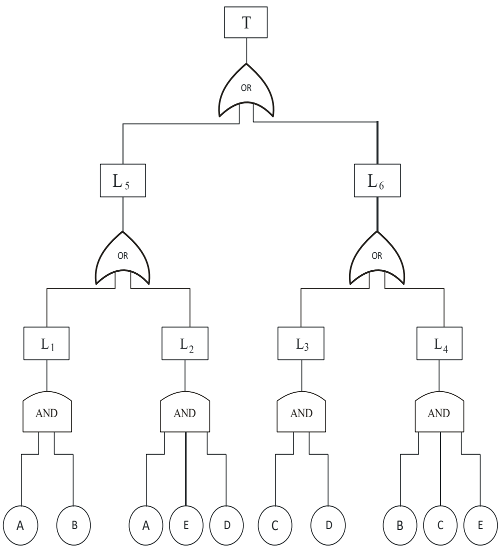


Fig. 2. Fault Event Diagram of the Block diagram of the system

An AND gate is approximately the intersection of the input of an event sets, hence, the output probability of an AND gate is given by Eq. 3 (Boryczko et al., 2022; Sonawane et al., 2023).

$$P(A \; and \; B) = P(A \cap B) = P(A).P(B) \tag{3}$$

An OR gate on the contrary, correspond to a set of unions output that is given by Eq. 4.

$$(A \; or \; B) = P(A \cup B) = P(A) + P(B) - P(A \cap B) \tag{4}$$

Using the Boolean algebra, the probability of the top even $P(T)$ as shown in Fig. 2 is obtained as follows (Boryczko et al., 2022; Sonawane et al., 2023):

$$P(L_1) = P(\bar{A}_{WT} \cap \bar{B}_{PV}) = P(\bar{A}_{WT}).P(\bar{B}_{PV}) \tag{5}$$

$$P(L_2) = P(\bar{A}_{WT} \cap \bar{D}_{WT} \cap \bar{E}_{BAT}) = P(\bar{A}_{WT}).P(\bar{D}_{WT}).(\bar{E}_{BAT}) \tag{6}$$

$$P(L_3) = P(\bar{C}_{Inv1} \cap \bar{D}_{Inv2}) = P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}) \tag{7}$$

$$P(L_4) = P(\bar{B}_{PV} \cap \bar{C}_{Inv1} \cap \bar{E}_{BAT}) = P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{E}_{BAT}) \tag{8}$$

$$P(L_5) = P(L_1 \cup L_2) = P(L_1) + P(L_2) - P(L_1).P(L_2) \tag{9}$$

$$= P(\bar{A}_{WT}).P(\bar{B}_{PV}) + P(\bar{A}_{WT}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) - P(\bar{A}_{WT}).P(\bar{B}_{PV}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) \tag{10}$$

$$P(L_6) = P(L_3 \cup L_4) = P(L_3) + P(L_4) - P(L_3).P(L_4) \tag{11}$$

$$= P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}) + P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{E}_{BAT}) - P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) \tag{12}$$

The probability of the top event is given by Eq.13 (Sonawane et al., 2023)

$$P(T) = P(L_5 \cup L_6) = P(L_5) + P(L_6) - P(L_5).P(L_6) \tag{13}$$

$$\begin{aligned} &= P(\bar{A}_{WT}).P(\bar{B}_{PV}) + P(\bar{A}_{WT}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) \\ &-P(\bar{A}_{WT}).P(\bar{B}_{PV}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) + P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}) \\ &+ P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{E}_{BAT}) - P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) \\ &-\{[P(\bar{A}_{WT}).P(\bar{B}_{PV}) + P(\bar{A}_{WT}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) - \\ &P(\bar{A}_{WT}).P(\bar{B}_{PV}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT})] \\ &\times [P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}) + P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{E}_{BAT}) - \\ &P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT})]\} \end{aligned} \tag{14}$$

$$\begin{aligned} &= P(\bar{A}_{WT}).P(\bar{B}_{PV}) + P(\bar{A}_{WT}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) - \\ &P(\bar{A}_{WT}).P(\bar{B}_{PV}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) + P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}) \\ &+ P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{E}_{BAT}) - P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) - \\ &P(\bar{A}_{WT}).P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}) \\ &- P(\bar{A}_{WT}).P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{E}_{BAT}) - P(\bar{A}_{WT}).P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) \\ &+ 2P(\bar{A}_{WT}).P(\bar{B}_{PV}).P(\bar{C}_{Inv1}).P(\bar{D}_{Inv2}).P(\bar{E}_{BAT}) \end{aligned} \tag{15}$$

Where $P(\bar{A}_{WT}), P(\bar{B}_{PV}), P(\bar{C}_{Inv1}), P(\bar{D}_{Inv2}) \; and \; P(\bar{E}_{BAT})$ are the failure probability of the components.

For identical components,

$P(\bar{A}_{WT}) = P(\bar{B}_{PV}) = P(\bar{C}_{Inv1}) = P(\bar{D}_{Inv2}) = P(\bar{E}_{BAT}) = P(\gamma)$, then from Equ. 14, $P(T)$ is given by (Ahlawat et al., 2019):

$$P(T) = (P(\gamma))^2 + (P(\gamma))^3 - (P(\gamma))^4 + (P(\gamma))^2 + (P(\gamma))^3 - (P(\gamma))^4 - (P(\gamma))^4 - (P(\gamma))^4 - (P(\gamma))^4 + 2(P(\gamma))^5 \quad (16)$$

$$P(T) = 2(P(\gamma))^2 + 2(P(\gamma))^3 - 5(P(\gamma))^4 + 2(P(\gamma))^5 \quad (17)$$

If the failure of the component follows Weibull distribution, the reliability of its ith component is illustrated by (Ahlawat et al., 2019):

$$R(t) = e^{-\lambda\left[\frac{t^{\beta+1}}{\beta+1}\right]} \quad (18)$$

The top event probability then becomes

$$P(T) = 2\left(1 - e^{-\lambda\left[\frac{t^{\beta+1}}{\beta+1}\right]}\right)^2 + 2\left(1 - e^{-\lambda\left[\frac{t^{\beta+1}}{\beta+1}\right]}\right)^3 - 5\left(1 - e^{-\lambda\left[\frac{t^{\beta+1}}{\beta+1}\right]}\right)^4 + 2\left(1 - e^{-\lambda\left[\frac{t^{\beta+1}}{\beta+1}\right]}\right)^5 \quad (19)$$

Therefore, the reliability of the system is illustrated by:

$$R_s = 1 - P(T) \quad (20)$$

3. RESULTS AND DISCUSSION

The system's reliability has been assessed for various parameter values including failure rate (λ), shape parameter (β), and operating time (t). The graphical representation of the findings is displayed in Figs. 3 to 5, along with information presented in Table 1. Fig. 3 shows how the reliability of a system is impacted by λ, β, and t of the system components using Weibull failure laws. The system's reliability decreases as the failure rate (λ), shape parameter (β), and operating time (t) of the components increase. As depicted in Fig.3, with the failure rate being constant for all components, the system reliability decreases as β increases from $\beta = 0.1$ to $\beta = 0.2$. Also as shown in Fig.3, with a constant shape parameter of $\beta = 0.2$, the reliability of the system also decreases from when $\lambda = 0.01$ to $\lambda = 0.02$. Hence, this figure shows the impact of failure rate as a major critical influencer of reliability than shape parameter (Malik et al., 2020). Fig. 4 presents a graph of reliability versus failure rate, showing the effect of time and shape parameter on system reliability. This figure shows that the reliability of the system decreases with increase in time and shape parameters. Furthermore, the figure shows the critically of time as a major contributing factor than shape parameter in reliability of a network. Fig. 5 illustrates the plots of reliability against shape parameter, with the impact of time and failure rate on reliability. This figure shows a decrease in system reliability with both time and failure rate increase. Additionally, the figure shows that time plays a more significant role than failure rate in reliability analysis (Malik et al., 2020).

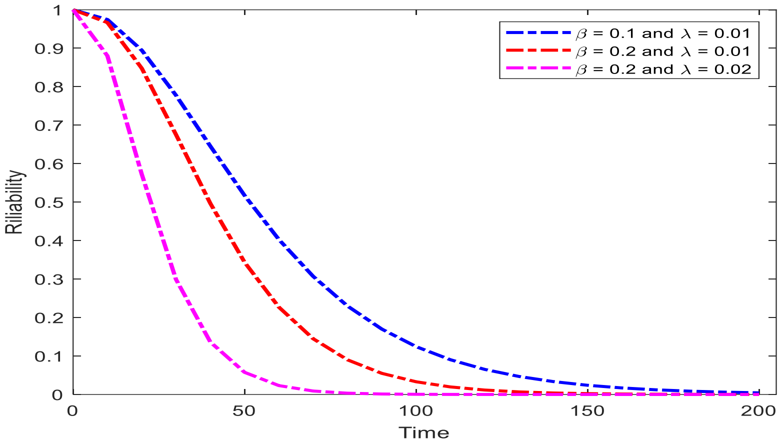


Fig. 3. Graph of Reliability vs time with varying failure rate and shape parameter

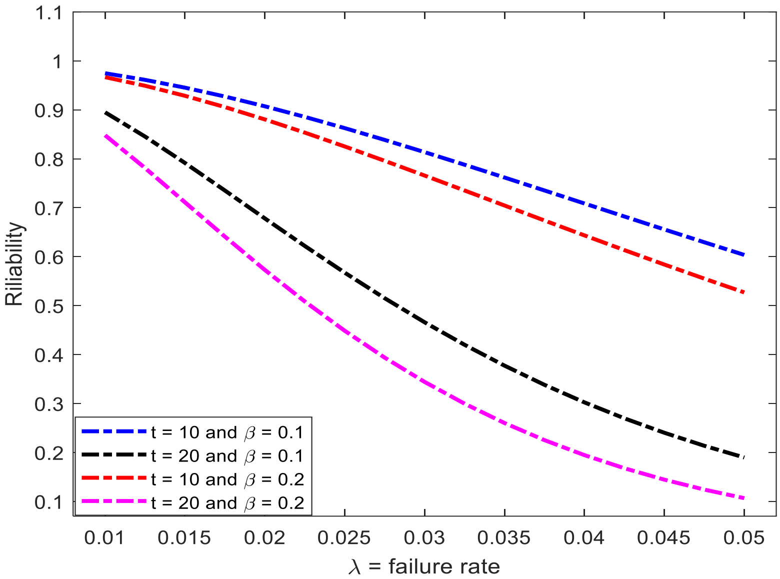


Fig. 4. Graph of reliability vs failure rate with varying shape parameter and time

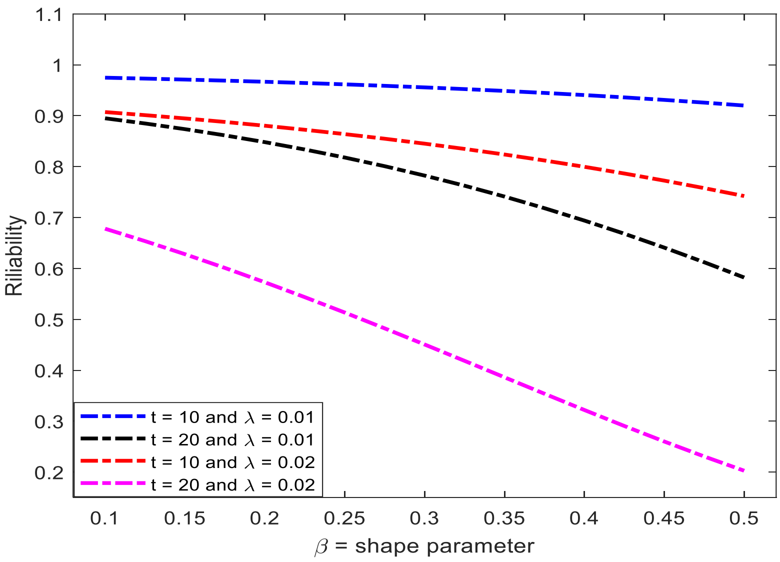


Fig. 5. Graph of reliability vs shape parameter with varying failure rate and time

The sensitivity of reliability of the system to λ, β and t is presented in Table 1. It can be inferred from this table that reliability decreases with increase in failure rate, shape parameter and system operating time (Malik et al., 2020). From Table 1, for $\lambda = 0.01$, the reliability of the system ranges from 0.97474 to 0.84816 for $\beta = 0.1$ to 0.2 and $t = 10$ to 20. For$\lambda = 0.02$, the reliability of the system ranges from 0.96671 to 0.57295 for $\beta = 0.1$ to 0.2 and $t = 10$ to 20. For $\lambda = 0.03$, the reliability of the system ranges from 0.95568 to 0.34419 for $\beta = 0.1$ to 0.2 and $t = 10$ to 20. For $\lambda = 0.04$, the reliability of the system ranges from 0.94058 to 0.19465 for $\beta = 0.1$ to 0.2 and $t = 10$ to 20. For $\lambda = 0.05$, the reliability of the system ranges from $0.92004$to 0.10677 for $\beta = 0.1$ to 0.2 and $t = 10$ to 20.

Table 1. Reliability vs failure rate, shape parameter and time of operation

Failure rate, λ	Reliability			
	β = 0.1, t = 10	β = 0.1, t = 20	β = 0.2, t = 10	β = 0.2, t = 20
0.01	0.97474	0.89498	0.96671	0.84816
0.02	0.96671	0.84816	0.88037	0.57295
0.03	0.95568	0.78245	0.76571	0.34419
0.04	0.94058	0.69408	0.64347	0.19465
0.05	0.92004	0.58224	0.52706	0.10677

Hence, the reliability of a system is inversely proportional to increase in failure rate, shape parameter and operating time of a component.

4. CONCLUSION

This paper presents the reliability evaluation of a complex renewable energy system consisting of solar, wind, battery and inverter system using the fault tree approach. The advent of clean renewable energy sources has become promising due to their abundant availability in society and the capacity for carbon-neutral economy that can mitigate climate change. However, as a result of their intermittent nature, hybrid renewable energy system is used to resolve this drawback. This paper presents a fault-tree approach to determine the reliability of complex hybrid renewable energy system with various failure rates, shape parameters, and operating time values, using Weibull failure laws. The proposed conceptual framework is examined. The results show that as the failure rate, shape parameter, and operating time increase, reliability decreases. The findings are presented both visually and through numerical data in the corresponding charts and graphs. The key findings of the research are as follows:

- With constant failure rate for all components, the system reliability decreases as β increases from $\beta = 0.1$ to $\beta = 0.2$.
- For constant shape parameter of $\beta = 0.2$, the system reliability also decreases from when $\lambda = 0.01$ to $\lambda = 0.02$.

- Time factor in reliability of a system is more critical than both shape parameter and failure rate.
- System reliability decreases with both increase in time and failure rate.
- Reliability of system is inversely proportional to increase in time of operation, shape parameter and failure rate.

Therefore, the research indicates that system reliability can be improved by operating the system at minimal values of failure rate and shape parameter.

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