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Reliability Evaluation of a Hybrid Renewable Energy Complex System with Weibull Failure Laws Using Minimal-Cut Set Approach

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ABSTRACT

Many rural areas in Nigeria are still grappling with epileptic power supply while others are awaiting access to the national grid due to their remote locations. To meet the essential energy demands at these areas, penetration of renewable energy sources has become a policy priority for the society and nation at large. Renewable energy sources are a viable alternative solution due to their abundant available nature, clean energy source, environmentally friendly, and emission -free. Due to their intermittent available property, hybrid renewable energy sources are used to mitigate this drawback. In this study, hybrid renewable complex energy system with five components subsystem is evaluated. The complex system was first converted to a series-parallel system using the Minimal-cut set approach. The variables associated with repair and failure rates of each component is assumed to follow a Weibull probability density function. The derivation of Mean Time to System Failure (MTSF) and reliability of the system was obtained via reliability mathematics techniques. The MTSF and reliability of the complex renewable system were calculated for random values of component parameters such as failure rate (λ), shape parameter (β) and operating time (t) of the system components. The dynamic responses of these reliability indices have been presented graphically and numerically with arbitrary numerical values of the component's parameters. The results reveal that reliability declines as failure rate, shape parameter, and operating time rise. The MTSF was also found to decrease with an increase in both failure rate and shape parameter of each system components. This study, therefore, shows that the system reliability can be increased by operating it at a minimal value of failure rate and shape parameter respectively.

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1. INTRODUCTION

Due to population increase, coupled with industrial revolution, Nigeria is facing a very high-energy demand like many other developing countries around the world [1]. In most rural communities, many inhabitants are still grappling with lack of electricity supply due to economic and environmental constraints, highly hilly areas of most rural communities make it not economically viable for grid extension, etc [2]. Most rural communities in Nigeria still depend on Fossil fuel usage for their energy supply. The use of Fossil fuel for energy usage is long overdue for replacement due to its recent high cost, harmful emission, and unpredictability of its abundance. Fossil fuel accounts for about 35.29% of emission pollution around the globe. Solar and wind energy sources
are one of the most abundant and clean energy sources in Nigeria that can reduce the burden created by Fossil fuel usage. Several local studies have shown that renewable energy sources are capable of solving the energy needs of most rural communities in Nigeria. To achieve the United Nation's (UN) sustainable development goal 7 (SDG 7) and socio-economic development, sustainable and uninterruptible electricity supply is crucial [3]. While most rural locations in Nigeria are still grappling with epileptic power supply others are yet to be supplied by the grid due to their remote locations. Renewable energy integration has been identified as one major way to solve this problem. Renewable energy sources have been seen as a viable alternative solution to mitigate the energy crisis in remote areas of Nigeria. For variety of reasons, countries have begun to focus on strategies to promote environmental sustainability and reduce CO_2 emissions, with special emphasis on renewable energy system [4–8]. Renewable energy source are very promising replacement energy source as a results of their available nature, continuous and enriched clean energy source properties. However, the sporadic and unpredictable nature of renewable energy sources is one of the drawbacks that limit their optimal utilization, resulting in low efficiency [9-10]. Since geographical condition and seasonal climate change affect solar and wind energy sources, combining multiple renewable system sources will provide a robust, secured and reliable electricity generation/production [11]. Hybrid renewable energy sources can help to solve the variability and intermittency issues associated with a single renewable energy technology [10]. The hybrid renewable energy system have shown remarkable contribution to electricity generation around the globe[12-13]. This increased generation has drawn the attention of stakeholders and investors for their financial involvement, which may be hindered by unexpected component failures, which would lead to system downtime. Hybrid renewable energy source that uses multiple renewable energy sources like solar and wind energy sources are more reliable than single source [10]. Hence, reliability of a multiple (hybrid) renewable energy system is necessary to ensure improve and reliable electricity generation.

Reliability of a system is its "ability to perform its intended functions considering specific conditions for a period of time" [14]. Reliability is often expressed as the probability that a system or component has correctly performed it required functions in time interval (t_0, t). In the last few decades, system designers/planners have proffered several ways of improving the connectivity of system components, which include series, parallel, parallel-series, series-parallel and mixed component connections [15]. The system reliability, therefore, needs to be determined to know the influence of system configuration on the system performance. It has been noticed that the reliability of series systems are much lesser than the reliability of its most worst component, while the reverse is the case for parallel systems [16]. There are quite a number of papers that have looked into system reliability. In [17], the reliability of a complex non series-parallel network was studied for an additional components using Rayleigh failure law. A study that looks into the reliability of a photovoltaic system with the effect of $k-out-of-n$ component was investigated by [18]. The influence of component configuration on system reliability studies for a large scale PV systems was analyzed by [19]. The reliability, maintainability as well as availability assessment of a PV-system with grid-connection using exponentially distributed function based on reliability block diagram (RBD) was investigated by [20]. The reliability assessment of a PV system considering inverter thermal characteristics using fault tree theory was studied by [21]. Reliability, availability and condition monitoring (RACM) assessment of a photovoltaic system of grid-interconnection using exponentially distributed function was investigated by [22]. Investigating the reliability of a water supply system through fault tree analysis was carried out by [23]. Fault tree approach was used for the assessment of reliability in a photovoltaic large-scale system [24]. Long term reliability based performance of a hybrid solar and wind power system by considering the reliability value of the renewable energy source components was investigated by [25]. In [26], evaluation of the reliability of a complex safety-critical system considering exponential failure laws using a matrix-based minimal paths was studied. The reliability function and MTSF of an electronics system with Weibull failure probability was investigated by [27,28]. A performance study involving long-term reliability assessment of Wind and Solar renewable energies was done by [28].

However, the reviewed studies have many limitations. Most of the reviewed papers do not consider a hybrid renewable energy system, most of the studies focus on either series-parallel or parallel-series system, or not complex configuration. Furthermore, the failure distribution considered was mostly exponentially distributed.

The main objectives of this study focuses on the reliability study of a complex non-series-parallel network with a focus on hybrid configurations and Weibull failure distribution, which has received little attention in the literature. A method of resolution to a more simplified form is necessary because the majority of the useful systems that are currently available are complex in nature. The minimal-cut set approach is a strategy for assessing complicated systems that cannot be reduced to a simple series-parallel system. This method is unique because it calculates a wide variety of reliability parameters and simplifies complex systems to a simple series-parallel network. The model expression for reliability and MTSF are obtained by considering identical components with arbitrarily values for the Weibull failure laws parameters.

2. MATERIALS AND METHODS

2.1 DESCRIPTION OF THE SYSTEM

The block diagram of the system considered in this study is a non-series-parallel system consisting of Solar PV, Wind turbine, battery and inverter component as shown in Figure 1. The PV panel or module convert solar energy into a DC power supply. The Wind turbine also convert Wind speed energy into a DC power supply. The battery system is used as a storage device in case of a hybrid (solar PV and Wind turbine) system failure. The inverter system is used to convert DC to AC power supply.

Section 2 presents the materials and methods including the mathematical formulations employed in this study. In section 3, the results obtained are presented and discussed while the concluding remarks are presented in section 4.

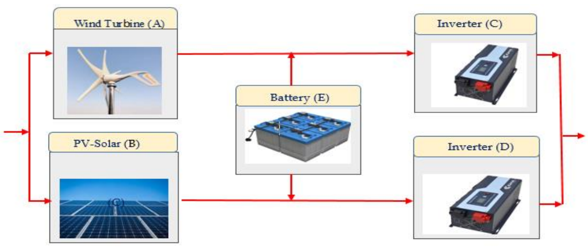

Figure 1: Reliability Block Diagram

When failure occurs in the wind section, the PV system is utilized as a backup energy source and vice-visa. Solar PV systems are typically designed to last 20-25 years. However, as illustrated in Figure 1, a hybrid system is required because PV systems are frequently subjected to a variety of environmental problems such as temperature, humidity, dust, rain, and etc.

2.2 THE MINIMAL CUT-SET METHOD

A cut-set configuration are set of components connected in parallel in which all components must fail for system failure to occur. Hence, a minimal cut-set is a set of minimum component failures that can cause the entire system to fail completely. From Figure 1, the minimal cut-sets are as follows in Eqn. (1).

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

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

For any singular cut-set, the components are seen in parallel, while the cut-sets are configured in series [26]. The cut-set matrix which has a number of rows equal to the number of cut-sets and the number of column equal to the number of components is given by

$$\begin{array}{c c} & \begin{array}{ccccc} A & B & C & D & E \end{array} \\ \begin{array}{c} C_1 \\ C_2 \\ C_3 \\ C_4 \end{array} & \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 \end{bmatrix} \end{array}$$

The system diagram from Figure 1 can be reduced to Figure 2 below.

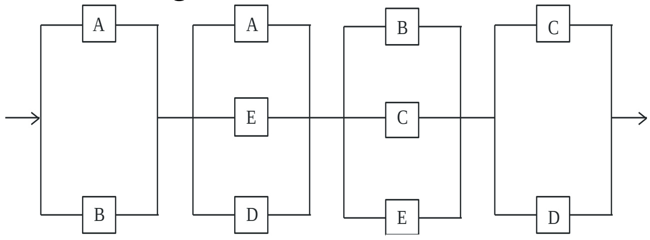

Figure 2: Cut-set diagram from reliability block diagram

The reliability of a series and parallel system component is given by Equations (2) and (3) below [28].

$$R_s(t) = \prod_i^n R_i(t) \qquad (2)$$

$$R_s(t) = 1 - \prod_i^n (1 - R_i(t)) \qquad (3)$$

Where R_i is the reliability of the i^{th} component $R_i (i = A, B, C.D, E)$.

Therefore, the reliability of the network from Figure 2 is given by Eq. (4) [26]:

$$R_s = [1 - (1 - R_{Wind})(1 - R_{Solar})] \times \left[1 - (1 - R_{Wind})(1 - R_{Battery})(1 - R_{Inveter2})\right] \times \left[1 - (1 - R_{Solar})(1 - R_{Inveter})(1 - R_{Battery})\right] \times [1 - (1 - R_{Inveter})(1 - R_{Inveter2})] \qquad (4)$$

$$= [1 - (1 - R_{Solar} - R_{Wind} + R_{Wind}R_{Solar}] \times \left[1 - (1 - R_{Wind})(1 - R_{Inveter} - R_{Battery} + R_{Inveter}R_{Battery})\right] \times \left[1 - (1 - R_{Solar})(1 - R_{Battery} - R_{Inveter} - R_{Inveter}R_{Battery})\right] \times [1 - (1 - R_{Inveter} - R_{Inveter2} + R_{Inveter}R_{Inveter2})] \qquad (5)$$

$$= [R_{Wind} + R_{Solar} - R_{Wind}R_{Solar}] \times \left[1 - (1 - R_{Inveter2} - R_{Battery} + R_{Inveter2}R_{Battery} - R_{Wind} + R_{Wind}R_{Inveter2} + R_{Wind}R_{Battery} - R_{Wind}R_{Inveter2}R_{Battery})\right] \times \left[1 - (1 - R_{Battery} - R_{Inveter} + R_{Inveter}R_{Battery} - R_{Solar} + R_{Solar}R_{Battery} + R_{Solar}R_{Inveter} - R_{Solar}R_{Inveter}R_{Battery}\right] \times [R_{Inveter2} + R_{Inveter} - R_{Inveter}R_{Inveter2}] \qquad (6)$$

$$= \left[R_{Inveter2} + R_{Battery} - R_{Inveter2}R_{Battery} + R_{Wind} - R_{Wind}R_{Inveter2} - R_{Wind}R_{Battery} + R_{Wind}R_{Inveter2}R_{Battery}\right] \times \left[R_{Battery} + R_{Inveter} - R_{Inveter}R_{Battery} + R_{Solar} - R_{Solar}R_{Battery} - R_{Solar}R_{Inveter} + R_{Solar}R_{Inveter}R_{Battery}\right] \times [R_{Inveter} + R_{Inveter2} - R_{Inveter}R_{Inveter2}] \qquad (7)$$

$$= \left[R_{Wind} + R_{Solar}R_{Inveter2} + R_{Solar}R_{Battery} - R_{Solar}R_{Inveter}R_{Battery} - R_{Wind}R_{Solar}R_{Inveter2} - R_{Wind}R_{Solar}R_{Battery} + R_{Wind}R_{Solar}R_{Inveter2}R_{Battery}\right] \times \left[R_{Inveter} + R_{Inveter2}R_{Battery} - \right.$$

$R_{Inveter}R_{Inveter2}R_{Battery} + R_{Solar}R_{Inveter2} - R_{Solar}R_{Inveter2}R_{Battery} - R_{Solar}R_{Inveter}R_{Inveter2} + R_{Inveter}R_{Inveter2}R_{Battery}]$ (8)

$$= R_{Wind}R_{Inveter} + R_{Wind}R_{Inveter2}R_{Battery} - R_{Wind}R_{Inveter}R_{Inveter2}R_{Battery} - R_{Wind}R_{Solar}R_{Inveter2}R_{Battery} - R_{Wind}R_{Solar}R_{Inveter}R_{Inveter2} + 2R_{Wind}R_{Solar}R_{Inveter}R_{Inveter2}R_{Battery} - R_{Battery}R_{Inveter}R_{Inveter2}R_{Battery} + R_{Solar}R_{Inveter2} + R_{Solar}R_{Inveter}R_{Battery} - R_{Wind}R_{Solar}R_{Inveter}R_{Battery} \quad (9)$$

Assuming each components distribution function is governed by the Weibull failure laws [26], then the reliability for each of the network component can be expressed as [27]

$$R_i = e^{-\lambda\frac{t^{\beta_i+1}}{\beta_i+1}} \quad (10)$$

Where
$\lambda = failure\ rate$, $\beta = shape\ parameter$ and $t = time$.
Therefore, for $\beta_1 = \beta_2 \ldots = \beta$, the reliability of the system is given by Eq, (8)

$$R_s = e^{-[\lambda_A+\lambda_B]\frac{t^{\beta_i+1}}{\beta_i+1}} + e^{-[\lambda_A+\lambda_D+\lambda_E]\frac{t^{\beta_i+1}}{\beta_i+1}} - e^{-[\lambda_A+\lambda_C+\lambda_D+\lambda_E]\frac{t^{\beta_i+1}}{\beta_i+1}} - e^{-[\lambda_A+\lambda_B+\lambda_D+\lambda_E]\frac{t^{\beta_i+1}}{\beta_i+1}} - e^{-[\lambda_A+\lambda_B+\lambda_C+\lambda_D]\frac{t^{\beta_i+1}}{\beta_i+1}} + 2\,e^{-[\lambda_A+\lambda_B+\lambda_C+\lambda_D+\lambda_E]\frac{t^{\beta_i+1}}{\beta_i+1}} - e^{-[\lambda_B+\lambda_C+\lambda_D+\lambda_E]\frac{t^{\beta_i+1}}{\beta_i+1}} + e^{-[\lambda_A+\lambda_B]\frac{t^{\beta_i+1}}{\beta_i+1}} + e^{-[\lambda_B+\lambda_C+\lambda_E]\frac{t^{\beta_i+1}}{\beta_i+1}} - e^{-[\lambda_A+\lambda_B+\lambda_C+\lambda_D]\frac{t^{\beta_i+1}}{\beta_i+1}} \quad (11)$$

For identical components, we have $R_i(t) = R(t)$. Then the system reliability becomes:

$$R_s = 2\,e^{-2\lambda\left[\frac{t^{\beta_i+1}}{\beta_i+1}\right]} + 2\,e^{-3\lambda\left[\frac{t^{\beta_i+1}}{\beta_i+1}\right]} - 5\,e^{-4\lambda\left[\frac{t^{\beta_i+1}}{\beta_i+1}\right]} + 2\,e^{-5\lambda\left[\frac{t^{\beta_i+1}}{\beta_i+1}\right]} \quad (12)$$

The mean-time-to-failure can be expressed as presented in Eq. (10) [26]

$$MTSF = \int_0^\infty R_s(t)dt \quad (13)$$

$$= \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_A+\lambda_B)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} + \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_A+\lambda_D+\lambda_E)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} - \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_A+\lambda_B+\lambda_D+\lambda_E)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} + \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_C+\lambda_D)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} + \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_B+\lambda_C+\lambda_E)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} - \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_B+\lambda_C+\lambda_D+\lambda_E)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} - \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_A+\lambda_B+\lambda_C+\lambda_D)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} - \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_A+\lambda_B+\lambda_C+\lambda_E)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} - \frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_A+\lambda_C+\lambda_D+\lambda_E)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} = +2\frac{\Gamma(\frac{1}{\beta+1})}{[(\lambda_A+\lambda_B+\lambda_C+\lambda_D+\lambda_E)(\beta+1)^\beta]^{\frac{1}{\beta+1}}} \quad (14)$$

$$= \frac{\Gamma(\frac{1}{\beta+1})}{[\lambda(\beta+1)^\beta]^{\frac{1}{\beta+1}}}\left[\frac{1}{2^{\frac{1}{\beta+1}}} + \frac{1}{3^{\frac{1}{\beta+1}}} - \frac{1}{4^{\frac{1}{\beta+1}}} + \frac{1}{2^{\frac{1}{\beta+1}}} + \frac{1}{3^{\frac{1}{\beta+1}}} - \frac{1}{4^{\frac{1}{\beta+1}}} - \frac{1}{4^{\frac{1}{\beta+1}}} - \frac{1}{4^{\frac{1}{\beta+1}}} - \frac{1}{4^{\frac{1}{\beta+1}}} + \frac{2}{5^{\frac{1}{\beta+1}}}\right]$$

$$= \frac{\Gamma(\frac{1}{\beta+1})}{[\lambda(\beta+1)^\beta]^{\frac{1}{\beta+1}}}\left[2\left(\frac{1}{2^{\frac{1}{\beta+1}}} + \frac{1}{3^{\frac{1}{\beta+1}}} + \frac{1}{4^{\frac{1}{\beta+1}}}\right) - \frac{5}{4^{\frac{1}{\beta+1}}}\right] \quad (15)$$

3. RESULTS AND DISCUSSION

This section presents the results obtained for the MTSF and reliability of a complex hybrid renewable system configuration considered in this study. These are evaluated for arbitrary system values parameters, such as failure rate (λ), shape parameter (β) and operating time (t) of the system. The results are seen graphically in Figure 3 - 6 and in tabular form in Table 1. Figure 3 depicts the influence of λ, β and t of the components on the system reliability by considering the Weibull probability failure laws. It can be seen that the system reliability decreases as failure rate (λ), shape parameter (β) and operating time (t) of the components increase. As shown in Figure 3, with the shape parameter being constant for all components, the reliability of the system was highest at the least failure rate of $\lambda = 0.01$ and lowest at the most failure rate of $\lambda = 0.05$. This Figure shows that the reliability of the hybrid complex system decreases with an increase in λ of each component. Figure 4 also depicts the effect of λ, β and t of the components on the system reliability by considering the Weibull failure laws. It is observed that the system reliability decreases with increase in failure rate (λ), shape parameter (β) and operating time (t) of the components. As shown in Figure 4, with the failure rate being constant for all components, the reliability of the system was highest at the least shape parameter of $\beta = 0.1$ and lowest at the most shape parameter of $\beta = 0.5$. This Figure shows the reliability of the system being decreasing with increasing β of each components. This is a testimony that increasing failure rate, shape parameter and time are inimical to increase in reliability of a system.

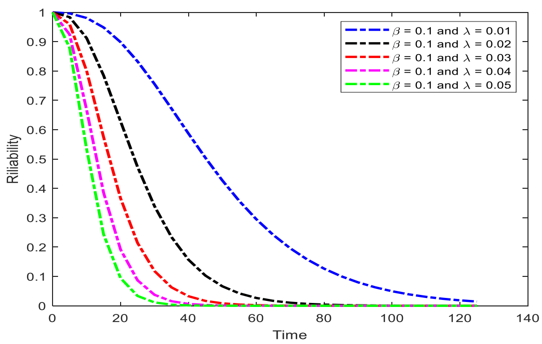

Figure 3: Graph of Reliability vs Time with Variable Failure Rate and Constant Shape Parameter

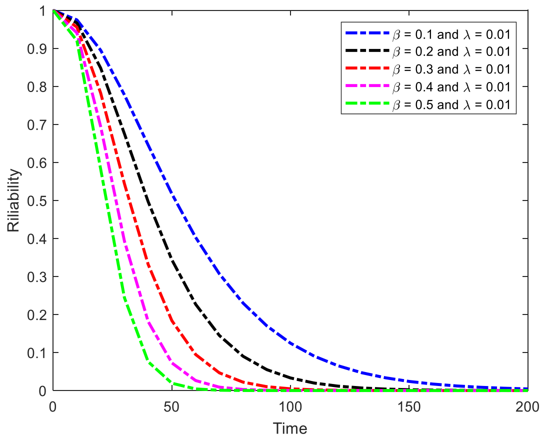

Figure 4: Graph of Reliability vs Time with Variable Shape Parameter and Constant Failure Rate

Figure 5 depicts the influence of λ and β of each component on the MTSF of the system by considering the Weibull failure laws. From this figure, it is seen that the MTSF of the system drops as failure rate (λ) and shape parameter (β) increase. As shown in Figure 5, with the shape parameter of the components being the highest at $\beta = 0.5$, the MTSF of the system was at it lowest value, while at $\beta = 0.1$, the MTSF was at it highest value. Figure 6 also depicts the influence of λ and β of the components on the system MTSF. It can be seen that the system MTSF decreases as failure rate (λ) increases. As shown in Figure 6, with the failure rate (λ) of the components being the highest at $\lambda = 0.05$, the MTSF of the system was at it lowest value, while at $\lambda = 0.01$, the MTSF was at its highest value.

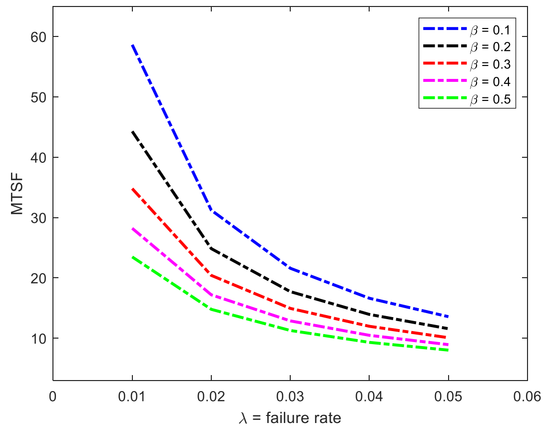

Figure 5: Graph of MTSF vs Failure Rate with variable Shape Parameter

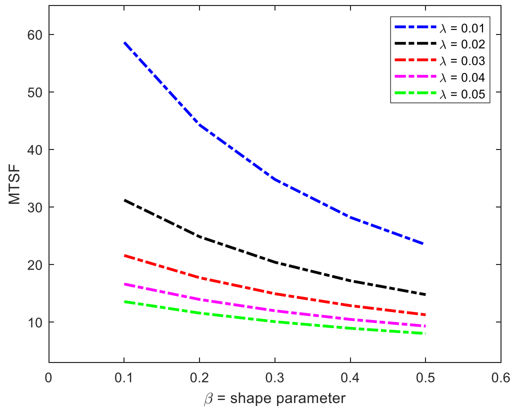

Figure 6: Graph of MTSF vs Shape Parameter with variable Failure Rate

The sensitivity of reliability and MTSF 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 time of operation of the system. Also from this table, it can be seen that MTSF decreases as failure rate and shape parameter increases. . These results can be validated by comparing with the results in [29].

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

λ	System Reliability				MTSF	
	β = 0.1, t = 10	β = 0.1, t = 20	β = 0.2, t = 10	β = 0.2, t = 20	β = 0.1	β = 0.2
0.01	0.97474	0.89498	0.96671	0.84816	58.62890	44.28171
0.02	0.96671	0.84816	0.88037	0.57295	31.22109	24.85227
0.03	0.95568	0.78245	0.76571	0.34419	21.59559	17.72651
0.04	0.94058	0.69408	0.64347	0.19465	16.62587	13.94786
0.05	0.92004	0.58224	0.52706	0.10677	13.57327	11.58109

4. CONCLUSION

Renewable energy sources are attractive energy sources due to their abundant available nature, highly clean energy source because of their environmental friendly nature and cheap continuous nature. However, because of their intermittent available property, hybrid renewable energy sources are used to counter this drawback. In this paper, assessing the reliability performance of a hybrid renewable energy complex system with arbitrary values of failure rate, shape parameter, and operating time by considering the Weibull failure laws was studied. The reliability and MTSF of the system was derived analytically in section 2 of this study. It is observed from the results that reliability decreases with increase in failure rate, shape parameter, and operating time. The MTSF was also observe to decrease with both increase in failure rate and shape parameter of each system components. The results are shown both graphically and numerically in the respective figures and table. This study, therefore, shows that the system reliability can be increased by operating it at a minimal value of failure rate and shape parameter respectively.

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