IE 4330 and 5330 Mid-term Project Report
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Project Title: A Lifecycle Approach to Solar Photovoltaic Reliability Management

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Abstract:

This report outlines a lifecycle approach to reliability management for large-scale photovoltaic (PV) systems, covering component reliability, system reliability modeling, spare parts management, and lifecycle cost analysis. It evaluates component reliability using statistical distributions and develops Reliability Block Diagrams (RBDs) for system-level analysis, particularly for extensive installations like the Desert Sunlight Solar Farm. An optimization model identifies configurations achieving at least 95% reliability over 20 years at a minimized cost of approximately $536 billion. Spare parts requirements are predicted using probabilistic models, ensuring efficient maintenance and high system availability. Finally, a lifecycle cost analysis confirms long-term profitability despite significant initial and maintenance expenses.

Introduction:

The adoption of solar photovoltaic (PV) technology has grown significantly as global efforts intensify to shift towards renewable energy sources. Ensuring the reliability and cost-effectiveness of large-scale PV installations remains critical to maximizing their long-term benefits and sustainability. Reliability management of these systems involves comprehensive analysis across multiple lifecycle stages, from component selection and system configuration to operational maintenance and eventual disposal. This report aims to address these reliability management aspects comprehensively by evaluating component reliability, developing robust system-level reliability models, predicting spare parts requirements, and conducting detailed lifecycle cost analyses. Special attention is devoted to large-scale systems such as the Desert Sunlight Solar Farm, exemplifying the complexity and importance of accurate reliability forecasting. By leveraging statistical reliability models and optimization strategies, the analysis identifies optimal configurations to balance performance reliability with economic feasibility, ensuring the systems' operational efficiency and financial sustainability. This lifecycle approach not only highlights the critical interplay between reliability and cost but also provides practical guidelines for decision-makers aiming to implement and maintain effective, resilient PV energy systems.

Methodology:

This project is segmented into four tasks:

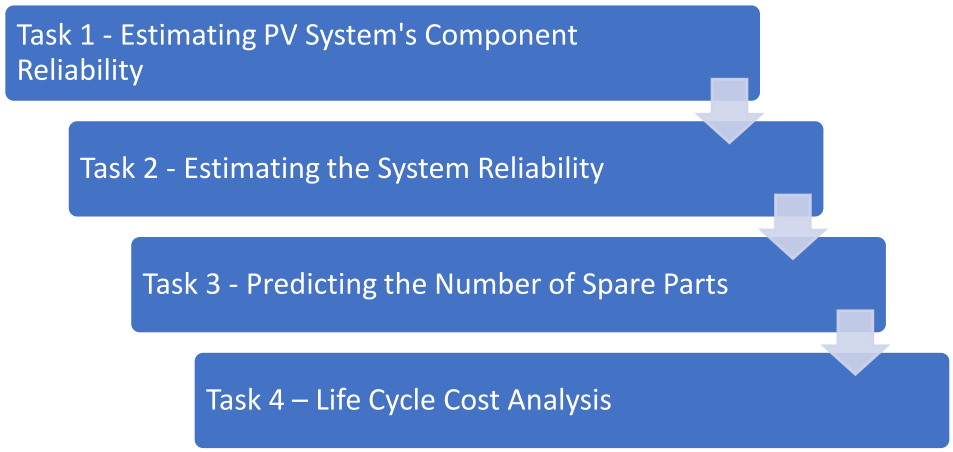

Figure 1: Methodology for the PV farm Reliability Analysis

Task 1 Estimating PV System's Component Reliability

Task 1 focuses on assessing the reliability of key PV system components: solar panels, charge controllers, inverters, and batteries. The objective is to determine their Mean Time Between Failures (MTBF) and select appropriate reliability models. Progress thus far includes gathering preliminary data from industry sources and reliability handbooks. Solar panels, known for longevity, exhibit MTBF values exceeding 25-30 years, though their efficiency degrades over time (NREL, 2020). Inverters and charge controllers, as electronic components, have shorter lifespans, with MTBF estimates ranging from 100,000 to 200,000 hours (approximately 11-22 years), based on standards like MIL-HDBK-217F (1991). Lithium-ion batteries, commonly used in PV systems, typically last 10-15 years, influenced by usage and environmental factors. For modeling, exponential distribution is suitable for components with constant failure rates, such as inverters and charge controllers, while the Weibull distribution better captures wear-out behaviors in batteries (O'Connor & Kleyner, 2012). Current efforts involve compiling manufacturer specifications and academic literature to refine these estimates. This foundational work will support system-level reliability analysis in subsequent tasks, ensuring accurate data drives the overall model.

Table1: Components Failure Data

Component	MTBF (Years)	Failure Rate (per year)	Distribution
Solar Panels	2,000	0.0005	Exponential
Charge Controllers	10	0.1	Exponential
Inverters	12	0.0833	Exponential
Batteries	10	0.1	Exponential

For exponential distribution the reliability of each component can be found by using the following formula:

$$R(t) = e^{-\lambda t} \qquad (eq1)$$

Where

λ is the failure rate of each component and t being the time.

Now the lifetime of PV system is generally expected to be 20-25 years, therefore the reliability after 20 years can be found by equation 1.

So, the reliability of solar panels after 20 years is:

$$R_{solar\ panel}(20) = e^{-0.0005*20} = .9905\ or\ 99\%$$

Similarly, all the components' reliability can be found using the same formula. Component reliability using Excel is given in table 2:

Table2: Components Reliability of the PV

Component	t (years)	R(t)
Solar Panels	20	0.99005
Charge Controllers	20	0.135335
Inverters	20	0.189002
Batteries	20	0.135335

Task 2: Estimating the System Reliability

Task 2 aims to estimate the overall reliability of the Desert Sunlight Solar Farm, which features 2,200,000 solar panels and supporting components like inverters and charge controllers. Given the system's scale, modeling each component individually is impractical. Instead, Reliability Block Diagrams (RBDs) are being developed to represent the system architecture. Groups of panels are treated as parallel blocks feeding into inverters, which may be configured in series or with redundancy. Progress includes applying standard reliability formulas: for series systems, reliability is the product of individual component reliability; for parallel systems, it is one minus the product of failure probabilities (Ebeling, 2009). Assumptions about inverter-to-panel ratios and redundancy are being tested to simplify the model. The current focus is deriving a system-level MTBF or time-dependent reliability function, using component data from Task 1. Challenges include determining realistic configurations for such a large system, but initial models suggest that redundancy in critical components like inverters could significantly enhance reliability. This intermediate analysis will inform spare parts predictions and cost assessments in later stages.

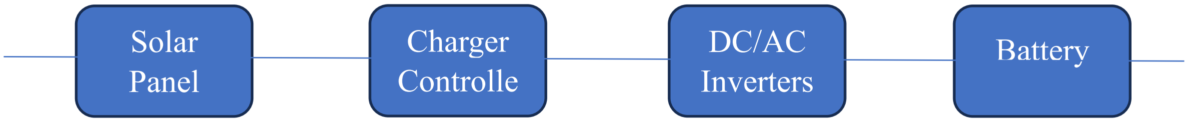

Figure 2: Series System Reliability Block Diagram of the PV

Now each component can be modeled as a parallel redundant subsystem then all together connected in series.

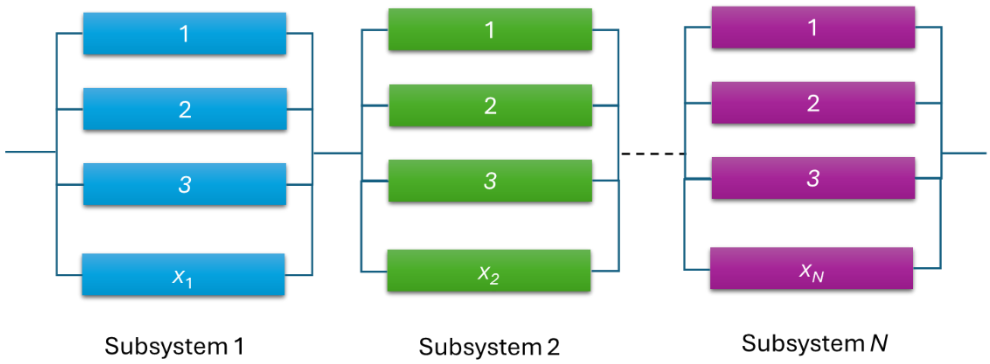

Figure 3: Series Parallel Reliability Block Diagram of the PV

Now as in task one we have computed all the parts reliability now we can easily calculate single PV system reliability, eventually we modeled an optimization problem where we want to achieve a minimum reliability of 95% with a minimum cost for the whole PV Farm , as we have 2,200,000 panels, these can be configured as a 22000 parallel strings of 100 PV connected in series. So, our decision variable is $x1$, $x2$, $x3$, $x4$ represents the number of redundant units for solar panel, charger controllers, DC/AC inverters and Batteries respectively. And the objective is to minimize the cost for a lifetime of 20 years for the whole PV park meeting the minimum reliability of the entire park of at least 95%. Using the excel Evolutionary solver we get an optimal solution.

Number of Redundant Unit		Component	t (years)	Component R(t)	Cost $	Subssytem (R_sub)	1 System (R_sys)	Total Cost
x1	2	Solar Panels	20	0.99005	640	0.999900998		1280
x2	56	Charge Controllers	20	0.135335	200	0.999709276		11200
x3	37	Inverters	20	0.189002	500	0.999569739		18500
x4	17	Batteries	20	0.135335	12500	0.915586101	0.914836	212500
								243480
	Number of PVs	Strings	PVs in Single Strings					
	2200000	22000	100					24348000
	Reliability of a single string com prised of 100 PV connected in Series					The Solar Farm Reliability		Total cost for the Solar Farm
	0.000136239					0.950086425		5.36E+11

Figure 4: Optimization result for Desert Sunlight Solar Farm reliability.

So, to get at least 95% reliability for the whole park for a 20-year lifetime, one PV system needs to configure with 2 solar panels, 56 controllers, 37 inverters, and 17 batteries in a series parallel setting, that minimize the cost of 536 billion USD.

Task 3: Predicting the Number of Spare Parts

Task 3 seeks to predict the spare parts required to maintain the PV system's availability over its lifetime. Using failure rates from Task 1, the expected number of component failures is being estimated. For example, with an inverter MTBF of 10 years and 100 inverters in the system, approximately 10 failures per year are anticipated. To account for randomness, the Poisson distribution is employed to model failure occurrences over time, providing a probabilistic basis for spare parts needs (Ebeling, 2009). Progress includes analyzing lead times for procurement and inventory holding costs to optimize stock levels. For instance, solar panels have low failure rates but long replacement times, while inverters require more frequent replenishment. The goal is to balance cost and availability, ensuring rapid recovery from failures. Current efforts focus on integrating Task 1's reliability data into these calculations and exploring safety stock strategies. This intermediate work lays the groundwork for a comprehensive spare parts management plan, critical to the system's lifecycle reliability. Here is the initial analysis and detailed analysis will be done eventually. The reliability graphs for the battery, inverter, and controller systems are presented, with the number of spare parts represented on the X-axis and system reliability on the Y-axis. The initially low reliability values suggest that a greater number of inverters and batteries will be required compared to controllers. As the number of spare parts increases, the reliability of the inverters and controllers improves significantly more than that of the batteries. This trend indicates that batteries represent the most critical point of failure in the system, highlighting the need for a larger inventory of spare battery components.

$$R_{paralell} = 1 - \prod_{i=0}^{n} n\,(1 - R_i)$$

TIME YEARS	TARGET R(t)
20	0.9

Solar Panel		Controller		Battery		Inverter	
Ri	.99005	Ri	.51343	Ri	0.13242	Ri	
	parallel		paralell		paralell		paralell
n	R	n	R	n	R	n	R
1	0.99005	1	0.513433	1	0.132416	1	0.263613
2	0.999901	2	0.763252	2	0.247298	2	0.457735
3	0.999999	3	0.884806	3	0.346967	3	0.600683
		4	0.943951	4	0.433439	4	0.705948
		5	0.972728	5	0.508461	5	0.783464
		6	0.98673	6	0.573548	6	0.840546
		7	0.993543	7	0.630017	7	0.88258
		8	0.998607	8	0.679009	8	0.913534
		9	0.998471	9	0.721513	9	0.936327
		10	0.999256	10	0.758389	10	0.953112
		11	0.999638	11	0.790382	11	0.965472
		12	0.999824	12	0.818139	12	0.974574
		13	0.999914	13	0.84222	13	0.981277
		14	0.999958	14	0.863113	14	0.986213
		15	0.99998	15	0.881239	15	0.989847
		16	0.99999	16	0.896965	16	0.992524
		17	----------- -	17	0.910608	17	0.994494
		18	----------- -	18	0.922445	18	0.995946
		19	----------- -	19	0.932715	19	0.997015
		20	----------- -	20	0.941624	20	0.997802
		21	----------- -	21	0.949354	21	0.998381
		22	----------- -	22	0.95606	22	0.998808
		23	----------- -	23	0.961879	23	0.999122
		24	----------- -	24	0.966927	24	0.999354

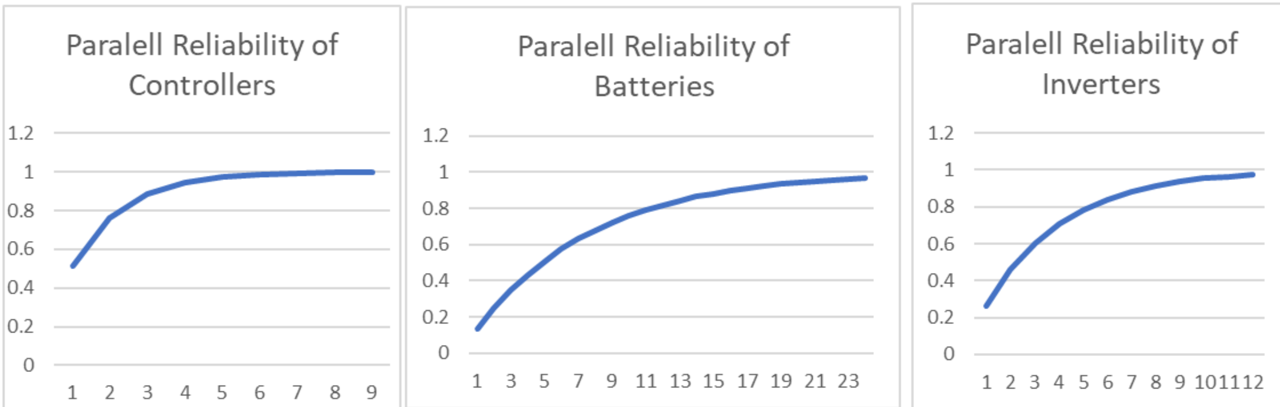

Figure 5: Component Reliability over time

The chart above illustrates the reliability values for a parallel system composed of controllers, batteries, and inverters. In this context, n represents the number of spare parts allocated for each component within the system. For each value of n, the corresponding system reliability is displayed, reflecting how the inclusion of additional redundant components enhances overall reliability. The data highlights how reliability improves as more spare parts are added, particularly in systems with parallel redundancy, where the system continues to function as long as at least one component remains operational.

a. $90\%\ Total\ PV\ System\ Target\ Reliability = \sqrt[3]{0.9} = R_{per\ system}(t) = 0.9655$

b. $R_{PV}(t) = 0.9723_{Controller} * 0.96188_{Battery} * 0.96547_{Inverter} = 0.90334\ or\ 90.33\%$

Using the formula above, we calculated the approximate reliability value of each system to allow for the entire PV system to have a reliability of 90% over 20 years. Using this approximation, we can find that we will need approximately 5 controllers, 23 batteries, and 11 inverters. Because the solar panels are so reliable, no spare parts are anticipated to be needed.

Task 4: Lifecycle Cost Analysis of 100 MW PV System

The analysis includes equipment cost, operating cost, inverter replacements, disposal cost, revenue from electricity generation, and net profit calculation.

Assumptions

- PV system size: 100 MW
- Capacity factor λ: 0.25
- Lifetime of system: 25 years
- Annual operating hours: 8,760 hours
- Discount rate: 5%
- Electricity sale price: $70/MWh

Lifecycle Cost Components

- Equipment Installation: $156 million
- Annual O&M Cost: $2.2 million/year
- Inverter Replacement: $10 million in Year 10 and Year 20
- Disposal Cost: $2 million

Annual Energy Output

The energy produced by the PV system each year is produced by:

$$E = \lambda \cdot t \cdot P_c$$

Where:

- $\lambda = 0.25$ is the capacity factor
- $t = 8760$ is the number of hours in a year
- $P_c = 100$ MW is the system capacity

$$E = 0.25 \times 8760 \times 100 = 219{,}000 \text{ MWh/year}$$

Annual Revenue

$$\text{Annual Revenue} = 219{,}000 \times 70 = 15.33 \text{ million USD/year}$$

Annualized Lifecycle Cost Calculation

We use the Capital Recovery Factor (CRF) to convert the Net Present Value (NPV) of total costs into an annual equivalent:

$$\mathrm{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where:

- $r = 0.05$ is the discount rate
- $n = 25$ years is the system lifetime

$$\mathrm{CRF} = \frac{0.05(1.05)^{25}}{(1.05)^{25} - 1} \approx 0.07095$$

Total lifecycle cost (NPV):

$$C_{\mathrm{NPV}} = 156 + 38.04 + 9.91 + 2 = 205.95 \text{ million USD}$$

Annualized cost:

$$\text{Annual Cost} = 205.95 \times 0.07095 \approx 14.62 \text{ million USD/year}$$

Profit Estimation

$$\text{Annual Profit} = \text{Revenue} - \text{Cost} = 15.33 - 14.62 = 0.71 \text{ million USD/year}$$

$$\text{Cumulative Profit over 25 years} = 0.71 \times 25 = 17.75 \text{ million USD}$$

Cumulative Revenue vs Cost:

Fig 6: Cumulative Revenue vs. Cumulative Cost Over 25 Years

Conclusion

The lifecycle cost analysis shows that the PV system can yield a total profit of approximately $17.75 million over 25 years. The largest expense is the initial capital cost, followed by maintenance and inverter replacements. Despite these costs, consistent annual revenue from energy sales ensures a profitable outcome. The lifecycle reliability management approach effectively balances reliability and cost for large-scale PV systems. The use of statistical reliability models and system optimization strategies significantly enhances operational efficiency and financial sustainability. Accurate prediction of spare parts and comprehensive lifecycle cost analyses further underline the practicality of this methodology. These insights serve as valuable guidance for stakeholders aiming to implement reliable and economically viable solar energy solutions.

Acknowledgement:

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