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Reliability analysis and life cycle costing of rooftop solar photovoltaic (PV) system operating in a composite environment

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Abstract. Solar PhotoVoltaic (PV) systems are becoming increasingly common, so it is critical to understand how system or component failure impacts lifetime costs. Reliability analysis uses historical performance data to help identify equipment or systems that perform badly. A case study of solar PV systems' dependability and Life Cycle Cost (LCC) analysis is presented in this research. Manufacturers and consumers of solar PV systems provide the information needed for reliability study. This research incorporates reliability analysis into the assessment of rooftop solar PV systems' LCCs in a composite climate. Failure and maintenance costs are a major contributor to total LCC, as demonstrated by estimating failure rates using Weibull++ modeling. ReliaSoft's Weibull++ software is used to estimate the best-fit failure distribution. Initial expenses, failure, Operation and Maintenance (O&M), and net salvage value are the categories into which the lifetime costs are divided. According to the analysis, inverters and balance-of-system elements are important sources of cost. The Mean Time Between Failure (MTBF) of earthing and grounding, DC CB, IGBT, AC CB, Grid, AC converter, relay, inverter, cooling fan, and SMBUS communication components is lower; however, since they need only modest repairs, this expense is covered by routine inspection. Understanding how costs affect a product's whole life cycle is made easier with the use of the LCC study. The cost of O&M accounts for around 74% of the overall LCC. Thus, it may be inferred that the LCC of the solar PV system was driven by O&M and failure costs. It gives the user an idea that O&M expenses associated with panel cleaning can be substituted by manual cleaning for small solar PV systems like those examined in this paper. Since failure costs are lower than O&M costs, it is possible to lower this cost by scheduling an ideal technician visit for routine inspection. The results indicate that PV system sustainability can be improved by implementing cost-effective technologies and optimizing maintenance procedures. Long-term performance monitoring, battery storage integration, and circular economy methods for recycling PV components should be the main topics of future research.

Keywords: Life cycle cost, Reliability analysis, MTBF, MTTR, Solar PV system, Maintainability.

Nomenclature

Abbreviation

AC CB	Alternating Current Combiner Box
ACDB	Alternating the Current Distribution Box
DC CB	Direct Current Combiner Box
EPBT	Energy PayBack Time
IGBT	Insulated-Gate Bipolar Transistor
LCC	Life Cycle Costing
LCCA	Life Cycle Cost Analysis
LCOE	Levelized Cost of Energy
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
O&M	Operation and Maintenance
ROI	Return on Investment
SMBUS	System Management Bus
TBF	Time Between Failure
TTR	Time to Repair

Symbol

C_a	Initial cost
C_m	Module cost

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C_{in}	Inverter cost
C_{lc}	Labor charges for installation and accessories
C_{mc}	Mounting and civil work cost
C_{ec}	Electrical work cost
T_{d}	Design life in years
C_{o}	Operation and Maintenance cost
C_{i}	Regular inspection labor cost
C_{c}	Panel cleaning cost
C_{f}	Failure cost
C_{nsv}	Net salvage value

1 Introduction

Reliability analysis is a useful concept for assessing the endurance and quality reliability of products. The likelihood that a system, substance, process, or gadget will carry out its intended function continuously for a predetermined amount of time when it does lawful business in the environment is known as reliability. Reliability analysis aids in the management of product/system failures during Life Cycle Cost (LCC) analysis, which examines the financial impact of a system or product across its lifetime. For many goods and services, reliability is a major risk since inconsistencies will unavoidably result in negative consequences. Reputation and goodwill, safety, competitiveness, profit margins, maintenance, and repair costs, and more can all be negatively impacted by unreliability. Reliability is concerned with reducing the frequency of failures over time and quantifying the probability of a failure-free operation. Due to increased competition, complex product design and development, the use of more sophisticated manufacturing techniques, particularly in defense and space technologies, and a growing focus on customer satisfaction, reliability has recently attracted a lot of attention. As the size and complexity of systems and equipment continue to increase, the impacts of failure worsen. Even though solar Photo Voltaic (PV) systems are being adopted worldwide, research on reliability analysis and comprehensive LCC remains limited. Many existing studies concentrate on either financial modeling or system dependability separately, but no integrated approach evaluates both technical and economic reliability factors. Moreover, comprehensive analyses of failure costs derived from actual field failure data are seldom conducted, even though general maintenance costs have been taken into account in previous studies. This study addresses this gap by incorporating reliability analysis into the evaluation of LCC of rooftop solar PV systems within a composite climate. This study's unique contribution is found in:

- A comprehensive investigation of failures in components of PV systems (*e.g.*, power conditioners, inverters, and balance-of-system elements) based on real failure data.
- Weibull++ reliability modeling serves to calculate the Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR), in addition to identifying failure distributions.
- Optimization of maintenance strategies to reduce operational and breakdown costs, along with practical recommendations for improving the cost-effectiveness of PV systems.

Failure of equipment or systems can have a major impact since they are getting bigger and more complicated. Reliability study should, therefore, highlight any systems or goods that are less dependable for the suggested design. It is crucial to choose relevant data and trustworthy analyses. Its products' low cost of living will undoubtedly give a rapidly expanding company a competitive edge over its rivals. Considering the solar PV system's reliability, an LCC analysis is advised. The primary goal of this study is

- To evaluate the best-fit probability distribution and hazard rate function for various components of solar PV systems.
- To create a systematic method for examining the LCC of solar PV systems, including detailed cost analyses and optimization methods.
- To assess the life cost of solar PV systems and provide recommendations for efficient maintenance procedures and LCC optimization.

The format of the paper is as follows: An overview of relevant literature highlighting the applications and techniques is given in Section 2. Section 3 provides the methodology adopted for reliability analysis. Section 4 presents the LCC analysis approach. Section 5 illustrates the life cycle analysis using a case study. Section 6 highlights the guidelines for improving solar PV plant maintenance. Section 7 describes the result and discussion, and Section 8 concludes the paper.

2 Literature review

Solar energy is the most well-known and reliable renewable energy source, and it is the way of the future for India's energy supply [1]. Using methods and tools to measure and compare how human activity affects various items, including goods and services, is essential to sustainable development. Using mathematical and evolutionary models, research work improves the combination of rooftop PV and Building-Integrated PhotoVoltaics (BIPV) to minimize energy fluctuations and enhance grid stability [2]. In terms of both energy generation and environmental impact, commercial PV systems are growing more and more efficient, according to the research conducted. Still, there is potential for improvement, especially in the production phase, when it comes to lowering the carbon footprint [3]. Over the past 60 years, reliability assessment techniques have been commonplace while designing and managing simple to sophisticated engineering systems. Consequently, numerous research has been conducted with an emphasis on the systems' dependability study. The utilization of solar energy, the most significant and plentiful energy source on the planet, is only going to grow. Finding new and existing technologies and evaluating their effects on the environment are made easier by the Life Cycle Assessment (LCA) technique. According to the research, the production process for PV panels accounts for 80% of the embedded energy. Energy efficiency, product placement, installation, integrated design, and safety all have an impact on photovoltaic technology's lifetime performance. For thin-film and crystalline silicon PV systems, a comprehensive analysis and meta-analysis of the energy ROI (Return On Investment), embedded energy, and energy payback period were conducted [4]. Few studies examine the carbon emissions from Tanzanian, Rwandan, and Kenyan electricity systems, emphasizing the difficulties in decarbonizing them and offering policy suggestions [5]. Some research reviews the LCA of solar PV based power generation systems [6]. The study suggests a reactive voltage control approach to improve the reliability of PV inverters, lowering temperature variations and prolonging the life of IGBTs in solar systems [7].

A study carried out in Iran revealed a reliance on photovoltaic system maintenance expenses, particularly for power plants that presently supply inexpensive energy derived from Iranian fossil fuels. Since PV systems' payback duration exceeds their technical life expectancy, more government funding and subsidies are needed [8]. One-third less power is produced by 1 MW rooftop solar PV panels installed in southern India than is optimally anticipated. When the real electricity produced by solar PV panels is considered, the payback period increases by 70% to 120%. O&M-related data, which could result in an inaccurate financial value, is not included in ROI calculations based on optimal power-generating statistics. Thus, uptime efficiency should be the main focus of the solar design concept [9]. According to a study done in Bangladesh, solar systems have a seven-year energy payback period. Construction materials determine the energy investment for solar PVs. Replacement energy for solar photovoltaic systems is greater than investment energy [10]. Major metrics such as global warming potential, fossil fuel consumption, Energy Payback Time (EPBT), and CO_2 payback time were used to analyze a 100 kWp cadmium telluride photovoltaic (CdTe PV) power generation system in Malaysia. The outcomes were contrasted with a PV system made of crystalline silicon. CdTe photovoltaic systems outperform silicon-based ones in terms of energy return on investment [11]. For a solar PV system in Singapore, LCA and LCC Analysis (LCCA) are carried out. Since climate change may become a more significant risk, cost should not be the only factor considered when making decisions. To reach the yearly goal, built-up areas should be utilized efficiently. Given Singapore's limited landfilling territory, the disposal options for solar PV modules must be investigated [12].

China carried out LCA research on mc-Si modules, considering environmental impacts, energy demand, and EPBT over the PV system's whole life cycle, including all upstream operations. The most crucial stage of the life cycle, which has an impact on the environment, is the conversion of metallic silicon into solar silicon. Photovoltaic systems have been compared to other power generation methods. It is advised that polysilicon photovoltaic systems be built rather than exported from China, given that power plants generate most of the country's electricity. Lastly, based on solar radiation, appropriate locations in China were recommended, even if transit is more effective [13]. Few studies employ LCA to compare the state-of-the-art photovoltaic technologies and analyze the environmental impact of photovoltaic power production systems (PV) throughout their life cycle by GreenHouse Gas (GHG) emissions and energy payback time (EPT) [14]. The advantages of solar power generation for the environment in terms of reducing GHG emissions have been extensively covered in the literature [11, 14, 15]. However, despite their huge potential for emission reduction, solar power generation systems are not emission-free technologies since they share the environmental burden of other life cycle stages [16–19]. It has been proposed that, in the case of solar PV panels, the planning for recycling PV waste should begin at the production stage, when the PV design should be made to make it easier to decommission PV modules for recycling and reuse when their useful life is coming to an end [20].

Inadequate management of electric and electronic waste has resulted from the expansion of the electronic industries. It is essential to create environmentally friendly electronics, enhance garbage collection, recycling, and disposal, and forbid the export of used equipment to developing nations [21]. By being reused and recycled at the end of their useful lives, PV panels have the potential to release a massive supply of raw materials and other valuable components. Examining the possibilities of a solar energy system for developing countries using recycled components revealed that, because battery production would not have any impact, the environmental burden would be reduced by 40% [22]. Similarly, the potential recovery of silicon from PV waste is expected to reduce the cumulative demand for silicon in Italy, where the high demand for c-Si technology modules has increased the demand for high-purity silicon, from 17 Mt to 13.4 Mt by 2040 [23]. Similarly, PV waste mining may provide 72–80% of the raw materials required to meet Spain's PV module demand in 2050 [24]. By 2045, Mexico will produce 1.2 MT of PV garbage; if it has access to the most advanced recycling technology, 75% of that amount can be recovered and used to create PV anew [25]. Solar PV has the potential to accelerate the transition from the conventional linear economy to the new circular economy concept by maximizing financial gains and minimizing environmental effects. This would ensure that energy resources are kept available for use in the production cycle for as long as possible [26]. Even though each study discussed thus far was carried out in a separate nation, [27] a study was recently carried out in India to investigate the circular economy potential of solar PV waste during the End-Of-Life (EOL) phase. Hybrid LCA is used in certain studies to increase the LCA of solar systems by expanding the range of activities considered and taking into account the technology-driven dynamics of embodied energy and carbon emissions [28]. Case studies carried out in six Indian states demonstrate that solar power plants in India have a very high economic viability. The payback period, which is less than 8 years, is contingent upon the initial investment and the power purchase agreement rate. The economic viability of solar power projects in India is therefore very high [29]. Research investigates the effects of availability and performance ratio (PR) on PV system design choices and LCC. It distinguishes between availability, which measures the amount of time the plant is in operation, and the effects of PR, which lowers instantaneous efficiency. The study emphasizes how various elements have varying effects on LCC and design decisions [30]. To identify economically viable PV systems, including standalone systems, BIPV, and solar farms, this research uses LCC analysis to construct an economic assessment framework for PV systems. It highlights LCC's contribution to the creation of PV policies [31]. To create a tool to forecast overall LCCs, few studies explore important factors that influence solar PV pricing beyond system size. When examining price by location, it looks at whether smaller geographic resolutions are necessary [32].

The main challenges that many nations encounter while implementing the LCC technique are deficiencies in their organizational structures and technical regulations, especially concerning cost breakdown structures [33]. The review of the literature shows that a wide range of system types have been evaluated using reliability analysis approaches. Reliability analysis and LCCs have been shown to reduce costs and improve system efficiency. Numerous research has demonstrated how LCC is dependent on the payback time [7, 25, 26], energy payback period [35, 36], environmental impact, economic impact, and return on investment as shown in Table 1. To improve decision-making and sustainability outcomes, research addresses the difficulties in applying systems thinking in sustainability assessments and provides insights into possible future research directions, such as the necessity of better integrating tools, methodologies, and interdisciplinary collaboration [41]. LCC of solar PV systems is based on component reliability based on failure data, and repair data is required to see the component failure effect on LCC. Current research on LCC analysis of solar PV systems emphasizes the need for more economical technology developments and better maintenance plans. Over the last 5 years, research has focused on recycling strategies, smart monitoring systems, and battery storage integration. The integration of reliability analysis with LCC investigations, however, has not received much attention. This work expands on earlier studies by using economic modeling and real-time failure data. The LCC estimation of a 2.7 kw monocrystalline Solar PV system is performed in this paper using reliability analysis.

3 Methodology for reliability analysis

The reliability and maintainability of the system's subsystems and components determine how often a system fails over its lifetime. Throughout its design life, a repairable system may encounter several failures. The defective or malfunctioning parts or subsystems are fixed or replaced during preventative and corrective maintenance to return the system to an operational state. When a repairable system's failure rate remains constant, MTBF and MTTR, two crucial cost parameters, define the system's reliability and maintainability. This study's essential component is identifying and displaying the key stages in a repairable system's life cycle, as shown in Figure 1. In general, these stages will apply to all products. The maintenance and repair phase will end for nonrepairable systems.

Figure 2 provides a broad framework that may be used for various systems and LCC analysis of the product or systems. The LCC can be calculated by adding purchase, operation, support, corrective maintenance and repair expenses, and net salvage value. Everything from the system's conception to its installation and commissioning is included in the acquisition cost. It might cover the price of training and warranties. The system needs electricity and consumables to run smoothly and continuously after installation. Operational costs include electric energy, consumables, inspection, and monitoring subscriptions.

In addition, support expenses are calculated by factoring in labor, replacement parts, preventative maintenance, and fixed support. When analyzing Time Between Failure (TBF) and Time to Repair (TTR) data from solar photovoltaic systems, this methodology is used as a framework. TBF and TTR information for every component and subsystem has been gathered, arranged, and categorized. It may be necessary to fit a non-stationary model, such as the non-Homogeneous Poisson Process (NHPP) if typical statistical techniques for reliability analysis are rendered ineffective by inaccurate assumptions about the equality of the data. Furthermore, the obtained field data shows no trend. After identifying the reliability features, the criticality of each component can be ascertained using the concept of an important measure. In the process of quantifying system reliability, component significance analysis is an essential phase that pinpoints a system's vulnerabilities and recommends fixes to improve its reliability. A component's likelihood of being essential to the system's failure is measured by its component reliability. Enhancing the reliability of the component that will have the largest impact on reliability should be the first emphasis if a system's reliability needs to be raised. The LCC and concentrating on enhancing the dependability of individual components are two ways to improve the reliability of solar power systems in this study. Reliability analysis is performed using failure and repair data using Reliasoft Weibull++ software. The Weibull distribution, in contrast to conventional exponential or normal distribution models, can simulate a variety of failure characteristics, such as wear-out failures, random failures, and early-life failures. Kolmogorov-Smirnov (K-S) tests are used by Weibull++ to choose the best-fit distribution, guaranteeing a higher forecast accuracy for reliability. Weibull++'s ability to provide precise failure rate estimation, hazard rate modeling, and component significance ranking makes it a popular tool in engineering reliability. The Kolmogorov-Smirnov test or K-S test, is a powerful statistical method for comparing two probability distributions. In solar PV systems, this test is used to determine the best-fit distribution for components and subsystems. The analysis's methodology consists of the following steps:

Table 1. Literature summary related to life cycle costing.

Ref	Data source	Duration of data	Number of plants studied	Specification	Parameters considered	Major findings
[10]	Bangladesh's subdistricts of Paba in the Rajshahi district and Kalihati, Ghatail, and Bhuapur in the Tangail district	2016–2017	20	40, 50, 65, 75, 85 Wp	Energy payback time, cost payback period	6.53 and 7.57 years energy payback time, cost payback period 2.55–4.03 years
[29]	Rajasthan, Tamil Nadu, Gujarat, Andhra Pradesh, Karnataka, and New Delhi	2010–2020	06	3.3 MW, 1 MW, 10 MW, 15 MW, 10 MW, 5 MW	LCOE, LCE, LCC	The project's payback duration is less than 8 years, and it depends on the initial investment and the Power Purchase Agreement (PPA) rate. Techno-economic viability is strong in India.
[13]	ISO standards-based advice obtained from China's typical photovoltaic enterprises		single	200 Wp multi-crystalline silicon (multi-Si) m	Energy payback time and primary energy demand (EPBT)	Best-suited areas in China were proposed for installation.
[12]	Building rooftop in Singapore	1 year	36	2.7 kWp, monocrystalline	LCA, EPBT, LCCA	Fossil energy use and GHG emission factors were taken into account for LCA and LCCA
[11]	Malaysia	30 years	–	100 kWp CdTe PV (cadmium telluride photovoltaic)	Potential for global warming, use of fossil fuels, energy payback period, and CO_2 payback period	There is a 0.94-year energy payback time and a 0.76-year CO_2 payback time. The CdTe PV system has a higher energy return on investment than the Si system, and environmental factors are taken into account in the life cycle assessment.
[37]	China company, literature	–	–	mcSi	Environmental impact	Environmental impact: the shift in environmental impacts linked to the export of Chinese photovoltaic modules made of multi-crystalline silicon is considered.
[38]		2 years	–	3 kWp rooftop silicon PV plant	Repowering time (ecotoxicity, freshwater, land and resource usage, minerals, metals, climate change)	For the PV installations under investigation, the optimal repowering period is estimated to be between 15 and 21 years on average.

(Continued on next page)

Table 1. (Continued)

Ref	Data source	Duration of data	Number of plants studied	Specification	Parameters considered	Major findings
[9]	Southern India is warm and humid	1 year	3,773 panels	1 MW rooftop, mono-crystalline	LCCA, net present value (NPV), internal rate of return (IRR), simple payback period (SPP), and discounted payback period (DPP)	The payback period lengthens by 70–120%, and the actual power generated is roughly one-third less than ideal.
[8]	Iran (Tehran and Bandar Abbas)	–	–	3 kWp, Taiwan, polycrystalline	LCCA based on the payback period	The PV system's payback period is mostly influenced by its maintenance expenses; when current power rates and initial costs are taken into account, the payback period of PV systems is longer than their technical life span.
[39]	Phoenix, Arizona		7700	c-Si	Energy payback time	Environmental indicators such as emissions, land transformation, and water withdrawal were investigated in terms of LCC.
[40]	Field data from the Indian industry	20		m-Si, p-Si	GHG emission rate, energy return on investment (EROI), and energy payback time (EPBT)	Three phases of solar PV systems are considered: production, construction, and operation.
[34]	Solar plant in Bhubaneswar	1 year	80 panels	30.24 kW	Payback period	A machine learning model for solar power prediction was developed, and the LCC of the rooftop plant was calculated.
[29]	Solar plants in Karnataka, Gujarat, Andhra Pradesh, Tamil Nadu, New Delhi and Rajasthan	–	6 panels	3.3 MW, 1 MW, 10 MW, 15 MW, 10 MW	Payback period	For a project with a life cycle of about 25 years, the payback period is usually shorter than 8 years.

- Collecting, classifying, and analyzing data on failure and repair times for each component and fault.
- Analyzing data to confirm the assumption of independently occurring and identically distributed failures.
- Estimating each component's reliability and maintainability parameters.
- Estimating LCCs.
- Identify the crucial components and create a better maintenance strategy to improve reliability.

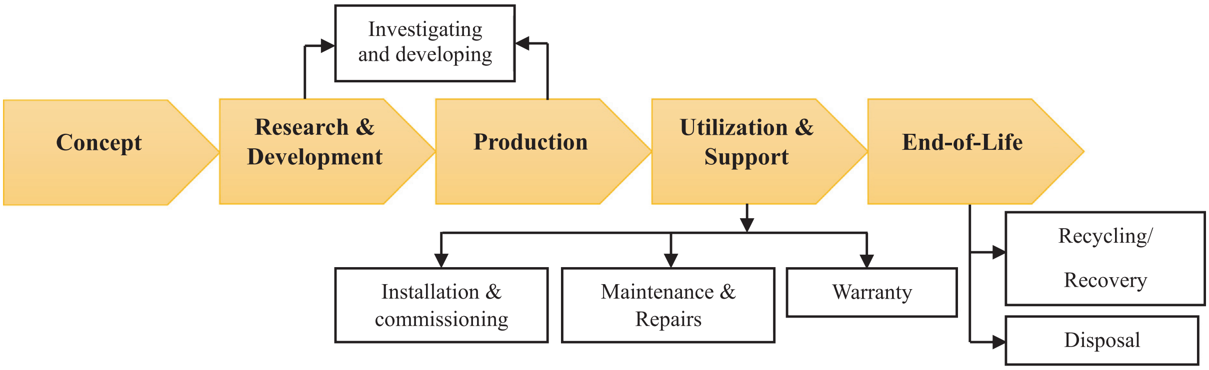

Fig. 1. Repairable system life cycle.

3.1 Data collection, analysis, and estimation of component reliability

Before data analysis to identify reliability features, three fundamental stages were completed. These include gathering data from solar sites and users of Solar PV systems, sorting the data necessary for analysis, and classifying the data in the format necessary for analysis. TBF, TTR, failure frequency, total breakdown, total working, and total maintenance hours are included. Data was collected from eight solar sites located in different places in India that were used for LCCA for panel aged 3–5 years. The data source includes: field measurements which include failure logs, maintenance reports, and replacements of components noted by site operators. Manufacturers of inverters and panels provide MTBF and warranty-based failure expectations. Details of the sites under study are given in Table 2. The data consists of polycrystalline solar panels of the same brand and same inverter make. The subsystem and component details of the solar system are given in Tables 3 and 4. To utilize statistical analysis and identify the tendency for failure, the TBF and TTR data for each machine component are organized in chronological order. This work presents the reliability analysis based on failure and repair data availability.

ReliaSoft's Weibull++ 2023 software has been used to estimate the best-fit distribution for every subsystem and component. The best-fit distribution for components and subsystems is determined using the K-S test. The best-fit distribution for components and subsystems with the parameters is shown in Tables 5 and 6. Additionally, it displays the MTTR and MTBF for components and subsystems.

Table 5 shows that the balance of the system, inverter, and protection subsystems have less MTBF, which means their failure frequency is higher. So, preventive maintenance is recommended for these subsystems.

Table 6 shows that earthing and grounding, DC CB, IGBT, AC CB, Grid, AC converter, relay, inverter, cooling fan, and SMBUS communication component show less MTBF, so they need more attention. In any solar system, components apart from solar panels are considered in balance of the system; as this is a comprehensive reliability study, the system is divided into different subsystems and components. The Inverter subsystem, which contributes more in total cost, has less MTBF, so regular monitoring is needed for the inverter.

It is found from Table 6 that the Inverter and power conditioning unit subsystems require considerable time for maintenance activities, followed by the balance of the system and protection system. These subsystems are critical from a maintainability perspective. The results of maintainability analysis are used to optimize system downtime. Relay and cooling fans have more MTTR values, requiring more maintenance time. These components are crucial from a maintainability point of view, so continuous monitoring is required.

4 Life cycle cost (LCC) analysis

One economic analysis tool for choosing options is the LCC. It determines the least expensive options for specific lifespans by comparing beginning investment possibilities [43]. The LCA technique can be used to determine whether a solar plant is energy sustainable if the energy produced over its operational life balances all the energy costs.

For solar photovoltaic systems, reliability data and component replacement and repair costs are used to estimate the life LCC analysis framework. There are four types of costs related to the life cycle of a solar PV system: capital, failure, decommissioning, and Operation and Maintenance (O&M) [44, 45]. In the investment costing, PV panels, electrical AC and DC, mechanical and civil installation, and peripheral works are all considered. Guidelines are mentioned here, but the cost of PV panel disposal has not been taken into account. When it comes to solar installations, PV panels and inverters are the costliest parts. This study attempts to calculate an LCC for Indian solar power projects. The economic viability of solar power plants has been noted; nonetheless, regulatory incentives and awareness campaigns are required to support renewable and sustainable energy sources.

Additionally, the research by the authors promotes and advances the use of solar energy within the Indian subcontinent and spreads knowledge about the techno-economic feasibility of solar power plants in India. Nevertheless, this study may not be comparable to previous research carried out in the Indian subcontinent because of the substantial differences in the geographical, meteorological, and

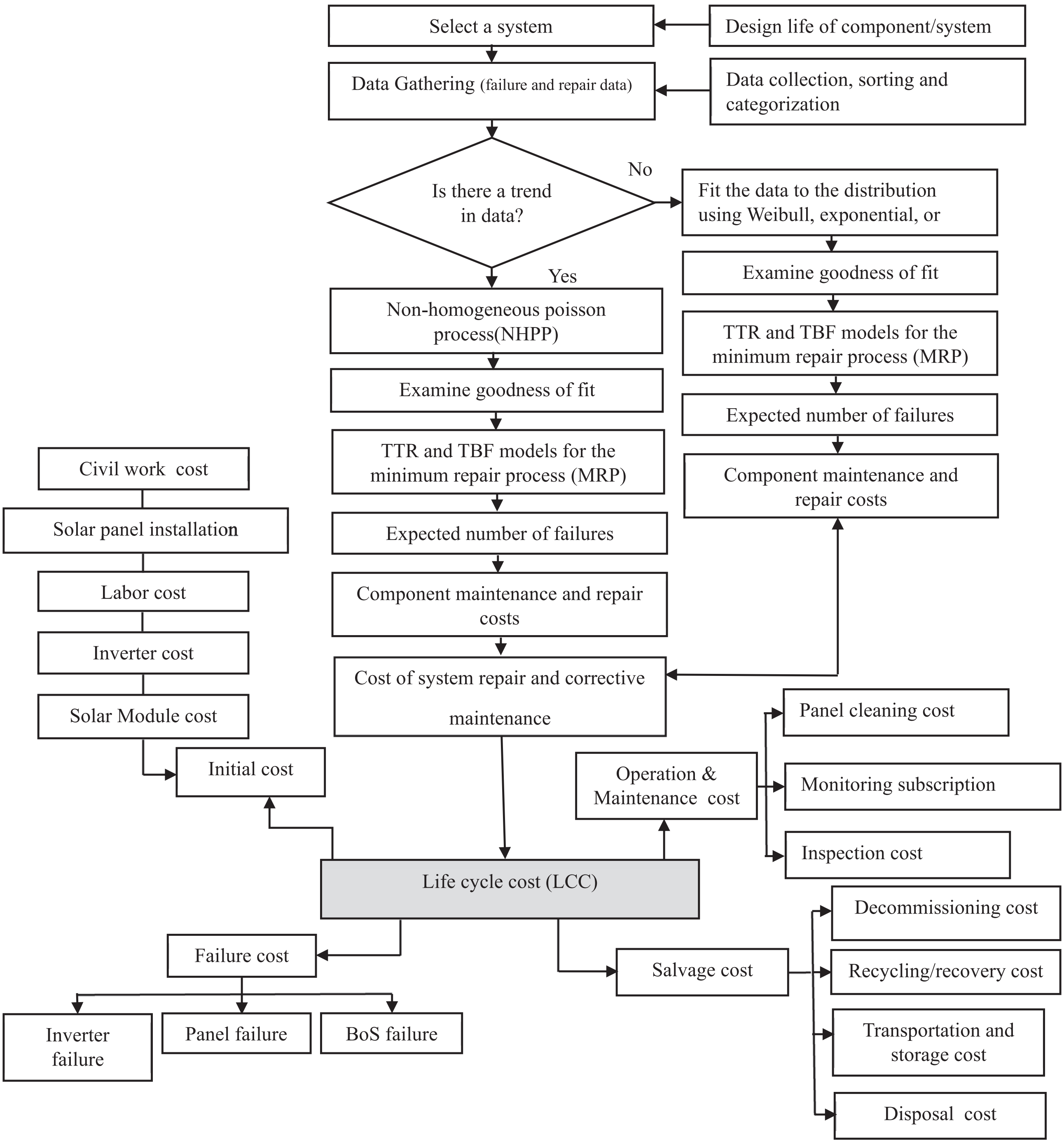

Fig. 2. Methodology for LCC analysis of repairable system [42].

environmental conditions outside of it. The baseline for the Indian subcontinent should be established by this study, and the results could be utilized to compare it to other research in the future.

4.1 Case study: 2.7 kW monocrystalline solar photovoltaic system

The cost distribution of a 2.7 kW monocrystalline rooftop-mounted solar PV system is given in Figure 3. The cost details of a 2.7 kW monocrystalline system with six panels mounted at an 18-tilt angle on the rooftop of the educational institute are taken here. Detailed specifications with cost details are given in Table 7.

Solar panels contribute more to the total cost of solar systems than other components. The typical cost distribution for solar systems is presented in Figure 4. It can be seen that solar panels and inverters contribute 45% and 30% of the total cost, respectively. Other costs include installation, mounting, labor cost, and electrical costs like cabling.

Table 2. Site details.

Site No.	Panel type	Installation year	Capacity (kW peak)
1	Polycrystalline	2020	9660
2	Polycrystalline	2020	2160
3	Polycrystalline	2020	2360
4	Polycrystalline	2020	1960
5	Polycrystalline	2020	8580
6	Polycrystalline	2021	10,700
7	Polycrystalline	2020	13,640
8	Polycrystalline	2019	1720

Table 3. Subsystem details.

Sr. No.	Subsystem name
1	Balance of the system
2	Inverter
3	Protection system
4	Storage system
5	String
6	Switching device
7	Power conditioning unit
8	Monitoring system

This percentage may vary depending on the inverter, panel used, installation area, ground-mounted, and rooftop-mounted. However, these two components still contribute more to the total cost. Each panel has a 450 W capacity and is attached to a separate solar panel. The methodology adopted for LCC is given in Figure 5.

4.2 Initial cost

It is simple to determine the system's initial cost. There is an abundance of material available for product initial cost estimation. The starting cost can be calculated using the sum of the costs of the different components (C_a). Concept creation, research and development, design and development, validation of products and systems, intellectual property, materials, quality control, and storage, manufacturing of components and subassemblies, assembly, reliability and life testing, analysis, diagnosis and rework, quality inspection and control, qualification and certification, packing and warehousing, transportation, distribution and delivery, training and documentation, modification of products and systems, guarantee/warranty cost, and additional costs [32, 41].

In a solar PV system, the initial cost is associated with the cost of solar modules (C_m), inverter (C_{in}), labor charges for installation and accessories (C_{lc}), solar panel mounting mechanical work [19], and civil work cost (C_{mc}), electrical work and electronic components (C_{ec}). Here, the cost includes transportation costs.

Table 4. Component details.

Sr. No.	Full form
1	Circuit breaker
2	Earthing and Grounding
3	DC central board
4	Wiring
5	Insulated-gate bipolar transistor
6	Fuse connect/Fuse
7	Printed circuit board
8	String monitoring box
9	Uninterruptible Power Supply
10	DC link
11	HT panel
12	Cooling fan
13	Transformer
14	Current transformer
15	AC Central Board
16	SMBUS Communication
17	Grid
18	AC Converter
19	Control system/Unit
20	SCADA communication
21	Connector
22	Relay
23	Inverter

$$C_a = (C_m) + (C_{in}) + (C_{lc}) + (C_{mc}) + (C_{ec}). \quad (1)$$

The above equation provides the generalized formula for calculating a solar system's initial cost.

4.3 Operation and maintenance (O&M) cost

Operation and Maintenance (O&M) cost refers to the entity needed for the system to function continuously [42]. The cost of panel cleaning, the cost of regular inspection, and the cost of labor care are the two cost components that have the biggest effects on the overall cost of operation in solar PV systems. So, the mathematical formula for calculating a system's operating costs considers these costs. Throughout the life of the PV system, the operational phase entails cleaning the panels and replacing or repairing any electrical or electronic components through regular inspection [40]. Operation cost involves mainly the cost of water for cleaning rather than labor for cleaning and periodic checkups by skilled manpower quarterly [46]. The operating cost is calculated based on cleaning the panels for a 2.7 kW system by semiskilled or skilled labor, which is 10,800 INR annually, considering once-in-a-month cleaning. Maharastra State Electricity Board (MSEB) charges for water neglected as a small solar system is considered here. C_i is a regular inspection labor cost, which includes the inspection of cables, electrical connections, and electronic components. It costs approximately 3000 INR per visit, a quarterly 12,000 INR annual cost.

Table 5. Best-fit distribution for subsystem using TBF and TTR data.

Sr. No.	Subsystem	Best fit distribution with parameters (for TBF)	Best fit distribution with parameters (for TTR)	MTBF (h)	MTTR (h)
1.	Balance of the system	2P Weibull: Beta = 1.25; Eta (h) = 113.47	Normal: Mean (h) = 1.64; Std (h) = 1.01	26.65	1.64
2.	Inverter	3P Weibull: Beta = 0.730583; Eta (h) = 6.378812; Gamma (h)= 21.7	1P Exp: Mean Time (h) = 5.28	105.68	5.28
3.	Protection system	Weibull 3P: Beta = 0.8; Eta (h) = 4.64: Gamma (h) = 21.7	Normal: Mean (h) = 1.69; Std (h)=1.03	267.87	1.30
4.	String	Normal: Mean (h) = 13,624; Std (h) = 12,288	1P Exp: Mean Time (h) = 0.88	13,624.00	0.88
5.	Power conditioning unit	Weibull 3P: Beta = 0.62; Eta (h) = 170.95; Gamma (h) = 21.94	Normal: Mean (h) = 3.99; Std (h) = 4.13	16,565	3.99

Table 6. Best-fit distribution for components using TBF and TTR data.

Sr. No.	Subsystem	Best fit distribution with parameters (for TBF)	Best fit distribution with parameters (for TTR)	MTBF (h)	MTTR (h)
1	Earthing and Grounding	Weibull 3P: Beta = 0.67; Eta (h) = 154.5; Gamma (h) = 21.76	Normal: Mean (h) = 1.66; Std (h) = 0.99	225.20	1.66
2	DC combiner box	2P Weibull: Beta = 0.98; Eta (h) = 467.39	2P Weibull: Beta=1.34; Eta (h)= 0.93	470.82	0.85
3	Insulated-gate bipolar transistor	2P Exponential: Mean Time (h) = 7.38; Gamma (h) = 20.02	2P Exp: Mean Time (h) = 0.90; Gamma (h) = 0.25	27.40	1.15
4	Fuse connect/ Fuse	Normal: Mean (h) = 16,804; Std (h) = 12,403.9	2P Weibull: Beta = 0.84; Eta (h) = 3.06	16,804	3.36
5	DC link	1P Exponential: Mean Time (h) = 17,463.54	2P Weibull: Beta = 0.96; Eta (h) = 1.77	17,464	1.80
6	Cooling fan	1P Exponential	3P Weibull: Beta = 4.69; Eta (h) = 10.26; Gamma (h) = 0.004	24	9.39
7	Transformer	Weibull 3P: Beta = 0.30; Eta (h) = 2513; Gamma (h) = 23.62	2P Exponential: Mean Time (h) = 5.1; Gamma (h) = 0.24	23,211	5.33
8	AC combiner box	2P Exponential: Mean Time (h) = 28; Gamma (h) = 15.74	Normal: Mean (h) = 1.83; Std (h) = 0.81	43.74	1.83
9	SMBUS Communication	Lognormal Log-Mean (h) = 6.25; Log-Std = 2.84	Lognormal: Log-Mean (h) = 0.62; Log-Std = 0.56	9.69	2.18
10	Grid	Weibull 3P: Beta = 0.53; Eta (h) = 57.68; Gamma (h) = 22.96	Normal: Mean (h) = 1.09; Std (h) = 0.45	128.55	1.09
11	AC Converter	3P Weibull: Beta = 0.36; Eta (h) = 19.63; Gamma (h) = 23.5	2P Exponential: Mean Time (h) = 0.05; Gamma (h) = 0.15	117.16	0.20
12	Connector	2P Weibull: Beta = 0.59; Eta (h) = 11,685	3P Weibull: Beta = 0.98; Eta (h) = 0.48; Gamma (h) = 0.04	57,731	0.53
13	Relay	1P Exponential	2P Weibull: Beta = 18.22; Eta (h) = 12.06	24	11.72
14	Inverter	3P Weibull: Beta = 0.41; Eta (h) = 109; Gamma (h) = 22.42	3P Weibull: Beta = 1.22; Eta (h) = 0.13; Gamma (h) = 0.15	354.36	0.27

Fig. 3. Rooftop-mounted monocrystalline solar PV system.

$$C_o = T_d \times [C_c + C_i] \quad (2)$$

Where C_c is panel cleaning cost in INR and C_i is regular inspection labor cost in INR. T_d is the design life of the solar system in years (25 years) [47].

Besides cleaning and regular inspection monitoring, subscription costs are added to O&M costs.

4.4 Failure cost (corrective maintenance cost) of solar PV system

The service life of a microinverter is 10 years, as per the warranty provided by the manufacturer. As can be seen from Table 6, for different components, MTBF and MTTR were calculated using reliability analysis done using field failure data. As per initial cost, the inverter is a component that contributes more to the total cost of the panel, and as can be seen from Table 6, the inverter has less MTBF. This means that the inverter has a higher failure rate and needs frequent repair or replacement activity. As per the expert opinion, 1.5–2.0% part replacement or repair activity per year is conducted for microinverters due to grid fluctuations in India. But this is taken care of in a warranty period of 10 years. This work considers inverter replacement costs every 10 years [48]. Referring to Table 6, other components apart from the inverter have lower MTBF values, which means the failure frequency is higher, but these have less contribution in total cost, which is taken care of under preventive maintenance, so it is considered 1%.

4.5 Salvage value

Sorting modules (such as thin-film versus c-Si, lead-bearing versus lead-free), transportation, and storage are all part of the end-of-life supply chain. Also, at the deployment site, balance-of-system components (racks, inverters, cabling, etc.) are separated, most of which will be sold into developed scrap metal and e-waste recycling markets [49]. In the Full Recovery End-of-Life Photovoltaic (FRELP) strategy, the whole cost of recycling, shipping, and disposal is subtracted from the benefit of the materials and energy recovered during the process. The entire cost can be further divided into private (investment, processing, and transportation fuel costs) and external (air, water, and land pollution) costs [50]. Analysis of an articulate framework for managing end-of-life photovoltaic panels was conducted, showing both its advantages and disadvantages from the standpoint of moving toward a circular economy. The conceptual framework outlines the primary technological and environmental ramifications of PV energy production and is founded on thorough Research and analysis of pertinent literature [51].

Table 7. Specification of solar PV system.

Parameter	Specification
Maximum power (P_{max})	450.0 W
Open circuit voltage (V_{oc})	50.10 V
Short circuit current (I_{sc})	11.46 A
Maximum power voltage (V_{mp})	41.81 V
Maximum power current (I_{mp})	10.77 A
Maximum system voltage	1500 VDC
Weight	23.80 Kg
Dimensions	2094 × 1038 mm

In general, salvage cost for solar plants is taken as 10% of the capital value at the end of 10 years if we take linear depreciation of, say, 10% per year. In this case, as the plant life is 25 years, the salvage value will theoretically be negligible and considered zero. It would usually be the value of scrapped material of the plant and can be taken as 3–5% of the capital cost based on expert opinion.

Reusing solar panels reduces waste and makes it possible to recover valuable and energy-intensive elements [52]. In one study, the silicon metal portion of the module was expected to be landfilled or burned, whereas the metal components of the module were assumed to be recycled [43, 44, 53, 54]. According to the study, this benefit would rise with increased use of recycled materials in PV components [55].

Glass, aluminum, copper, silver, and effectively recovered semiconductor materials are the usual components of solar panels. Approximately 80% of the weight of a standard solar panel is composed of glass and aluminum, which are easily recyclable materials. This recycling process and decommissioning process cost will again add money in salvage value. Decommissioning labor costs might be as low as half of installation labor costs [56]. Due to insufficient data and information, the salvage value is taken as zero here [57].

5 Life cycle cost analysis (LCCA) of solar PV system

The LCCA of the solar system is the total of the expenses related to purchase, operation, failure, support, and Net Salvage Value.

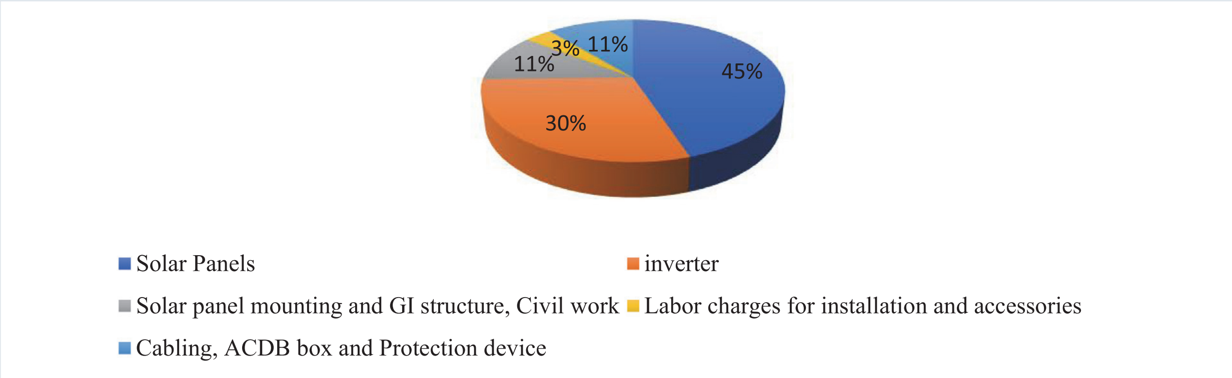

Fig. 4. Solar system cost distribution.

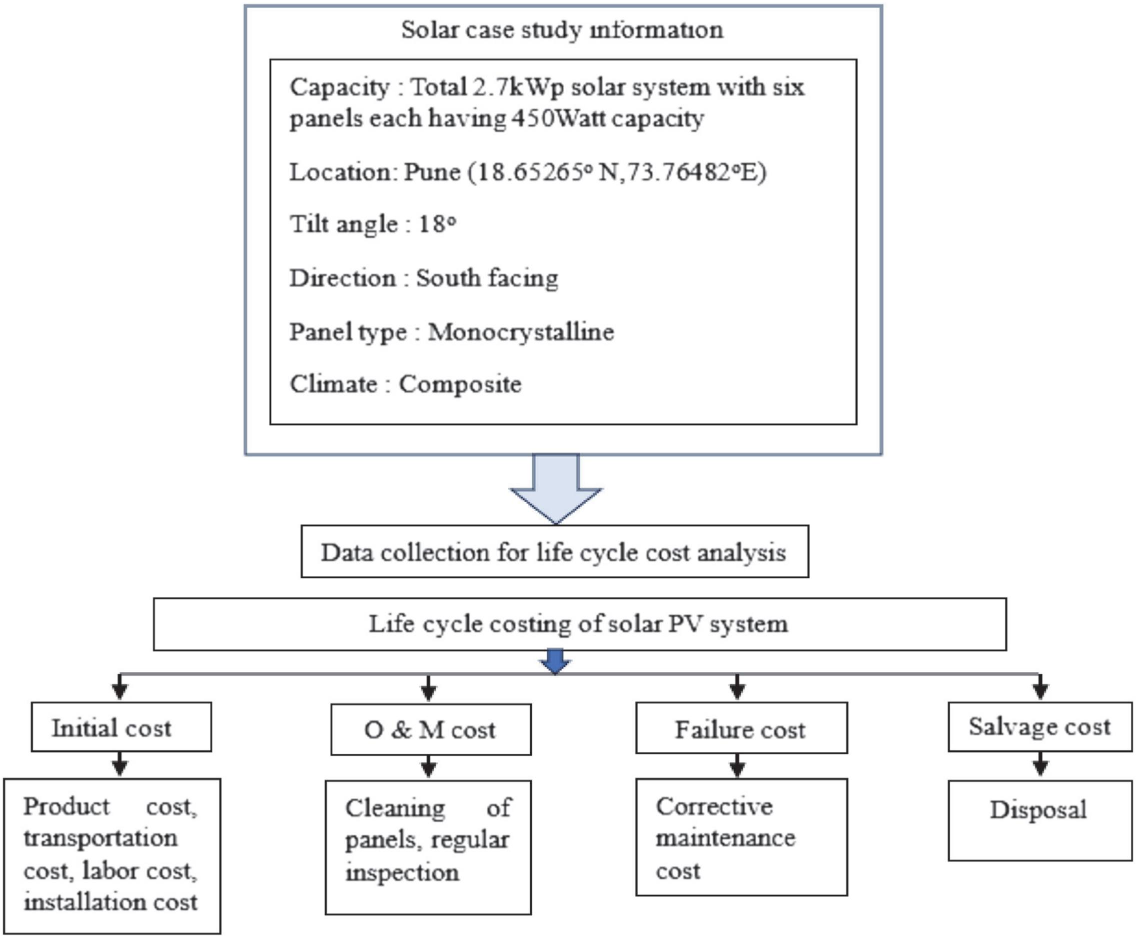

Fig. 5. Methodology adopted for life cycle costing.

$$\mathrm{LCC} = \text{Initial cost}\,(C_{\mathrm{a}}) + \text{Operation \& Maintenance cost}\,(\mathrm{C_o}) + \text{Failure cost}\,(C_{\mathrm{f}}) + \text{Net salvage value}\,(C_{\mathrm{nsv}})$$

$$\mathrm{LCC} = [C_{\mathrm{m}} + C_{\mathrm{in}} + C_{lc} + C_{\mathrm{mc}} + C_{\mathrm{ec}}] + T_{\mathrm{d}} \times [C_{\mathrm{c}} + C_{\mathrm{i}}] + C_{\mathrm{f}} + C_{\mathrm{nsv}}. \quad (3)$$

5.1 Initial cost of the solar PV system

In solar PV systems, the initial cost is associated with the cost of solar modules (C_{m}), inverter (C_{in}), labor charges for installation and accessories (C_{lc}), solar panel mounting mechanical work and civil work cost (C_{mc}), and electrical work and electronic components (C_{ec}). Wi-Fi/LAN connection charges are neglected as the system is so small. Therefore, the initial cost of the solar PV system is estimated as follows:

$$Ca = \text{cost of solar modules} + \text{inverter cost}$$
$$+ \text{Labor charges for installation and accessories}$$
$$+ \text{solar panel mounting mechanical work and civil work cost}$$
$$+ \text{electrical work and electronic components}$$
$$\text{(Cabling, ACDB box, and Protection device)}$$

$$C_a = 103{,}950 + 68{,}802 + 8000 + 25{,}300 + 25{,}428 = 231{,}480\,\text{INR}.$$

5.2 Operation and maintenance cost (O&M – C_o) of solar PV system

In the case of solar PV system operation, costs involve mainly the water for cleaning (considered mainly in large plants and taken as about 3–5 L/kW MIDC charges apply for water) rather than labor for cleaning and periodic checkups by skilled manpower quarterly. As this is a small system, water MSEB charges are neglected, and only panel cleaning and periodic checkups or inspection costs are considered. Inspection cost is associated with the technician visit cost, which is considered 3000 INR per visit, and a quarterly visit is scheduled here. Inspection of cables for loose connections, broken connections, electric supply, and electronic components are checked. Monitoring subscription is also considered in O&M cost. Operation and Maintenance cost estimation is given below.

1. Regular Inspections: Visual and electrical inspections – 12,000 INR per year (4 visits per year).
2. Cleaning: Cleaning service once in a month – 10,800 INR per year
3. Monitoring: Monitoring service subscription – No charges considered as the app is free for a lifetime.

$$\text{Annual O\&M cost} = 25 \times (10{,}800 + 12{,}000) = 5,70,000\,\text{INR}$$
$$C_o = 25 \times [10{,}800 + 12{,}000] = 5,70,000\,\text{INR}.$$

5.3 Failure cost (corrective maintenance cost) of solar PV system

The failure cost is estimated by reliability analysis of solar PV systems utilizing maintenance and failure data. The Relia soft Weibull++ software is used to determine the components' MTTF, distribution parameters, and best-fit distribution. The working hours of the solar system are 8760 h (considering daily 24 h). As seen from Tables 4 and 5, the inverter has a lower mean time between failure values, which denotes failure frequency, but the inverter has a 10-year warranty in which repair activity is taken care of. So, considering inverter replacement, after every 10 years, the replacement cost is calculated. The solar panel failure rate is 0.5% per year, which is estimated to be the failure rate of solar panels per year. As seen from Tables 5 and 6, the balance of the system means all the components apart from a solar panel and inverter failure frequency is higher, which is given in terms of MTBF. However, looking at the total cost contribution and their minor repairs, which can be covered under regular inspections, Bo's failure is taken as 1% per year. The LCC calculation for a site under study is given below.

5.4 Inverter replacement cost: (every 10 years) [48]

- Cost of Each Microinverter: 11,467 INR (6 microinverter cost = 68,802 INR).
- Number of Microinverters: 6.
- The lifespan of Microinverters: 10 years.
- System Life Cycle: 25 years.
- Inflation Rate or general price increase or price index: 2% per year [58].
- Technological Improvement or innovation rate or advancement rate: 1% reduction in cost per year.
- Discount Rate: 5% per year.

$$\text{Total Initial cost} = 68{,}802\,\text{INR}$$

$$\text{Future Cost} = \text{Initial Cost} \times (1 + \text{Inflation Rate})^{\text{Years}} \times (1 - \text{Technological Improvement Rate})^{\text{Years}} \quad (4)$$

The future cost at 10 years is calculated as follows:

Future cost per microinverter = 11,467 × (1.02^{10}) × (0.99^{10}) = 12,642 INR.

Total Future cost at year 10 = 6 × 12,642 = 75,852 INR.

The future cost at 20 years is calculated as follows:

Future cost per microinverter: = 11,467 × (1.02^{20}) × (0.99^{20}) = 13,937 INR.

Total Future cost at year 20 = 6 × 13,937 = 83,622 INR.

Present value cost at 10 years is estimated as follows:

Present value = $\frac{75{,}852}{(1.05^{10})}$ = 46,567 INR.

Present value cost at 20 years is estimated as follows:

Present value = $\frac{83{,}622}{(1.05^{20})}$ = 31,516 INR.

Sum of present value cost = 46,567 + 31,516 = 78,083 INR

- **Failure Rate for Panels**: 0.5% per year.

  As this system has six panels

1. Annual Panel Failure: 0.5% of 6 panels = 0.03 panels/year.
2. Total Panel Failures Over 25 Years: 0.03 panels/year × 25 years = 0.75 panels = 1 panel.
3. Replacement Cost: 17,325 INR.
4. Total Panel Failure Cost Over 25 Years: 1 panel × 17,325 = 17,325 INR.

Table 8. Inspection and maintenance check.

Sr. No.	Subsystem/Component	Things to inspect	Maintenance schedule	Repair/ Replace
1	Site	The array is not shaded	Monthly	Repair
		All debris from/around/under the array is removed.		Repair
2	PV module and solar array (including mounting structure)	All individual modules are cleaned	Monthly/ Annually	Repair
		No visual defects in the module		Replace
		No discoloration		Replace
		No indication of moisture penetration		Repair
		No indication of corrosion		Repair
		The array is firmly fixed.		Repair
		No loose or missing panel clamp		Repair
3	Wiring system	No mechanical damage to the cables	6 months	Replace
		Cable ties do not damage cables. Poor or mismatched connection.		Replace
		Connections are not frayed, loose, or corroded.		Replace
		Conduit ends are adequately sealed.		Repair
		Conduits and cables are firmly supported.		Repair
4	Electrical characteristics	Verify short circuit current	Monthly	Repair
5	Protective devices and isolators	Fuses and holders are still intact	Monthly	Repair
		MCB and RCD operate correctly		Replace
		The earthing system operates correctly.		Repair/ Replace
		Isolators function correctly		Repair
6	Labels and signs	Green PV label in place	During inspection	Replace
		The shutdown procedure is visible and readable.		Replace
		Disconnecting devices are adequately labeled.		Replace

- **Failure Rate for BOS**: 1% per year.

$$\text{BoS failure cost} = 0.01 \times 25{,}428 \times 25 = 6357\ \text{INR}.$$

- **Discount Rate**: 5% (optional).

The total LCC for a solar PV system for a lifespan of 25 years is calculated by summing up all the costs.

$$\text{LCC} = 2{,}31{,}480 + 5{,}70{,}000 + 78{,}083 + 17{,}325 + 6357 = 9{,}03{,}245\,\text{INR}.$$

Salvage value is not added here due to insufficient information and data. However, guidelines are provided in salvage cost details.

6 Guidelines for improving solar photovoltaic plant maintenance

Table 8 presents the probable maintenance schedule and repair/replacement required for components. This sheet is prepared based on the literature data, maintenance manual, and expert opinion. It also gives details about what the checkpoints should be component-wise/subsystems.

Table 9 presents the maintenance strategy [59] as per the failure modes observed in the solar system. This sheet is prepared by referring to literature data, maintenance manual, and reports as well as by taking expert opinions [59]. Field-observed failure modes are considered, and a maintenance strategy for each failure mode is recommended. This will provide a preventive maintenance strategy for the solar photovoltaic system components and recommend maintenance for faults. If solar arrays or panels are subjected to partial or periodic shading, system performance needs to be monitored, and panel placement should be optimized. Regular performance monitoring, inspection, and cleaning of the modules system will work efficiently, and loss of power can be avoided.

7 Result and discussion on LCC of solar PV system

The cost components of the solar PV system are shown in Table 10 based on the findings of the LCC analysis.

Table 9. Maintenance strategy as per failure modes.

Subsystem/Component	Potential failure mode	Maintenance strategy
Solar array	Partial shading	Frequent cleaning, observation, swapping out shaded panels, and optimizing panel layout.
	Periodic shading	Utilize shade analysis tools, arrange panels optimally, keep an eye on system performance, and clean the solar panels.
PV panel	Powder	Finding and fixing the underlying cause, washing the panels frequently, using water-repellent coatings or anti-soiling technology, performing routine maintenance, and implementing safety protocols.
Grounding/Lightning protection	Open or ineffective	The system should be tested, damaged components should be inspected, repaired, or replaced regularly, surge protection devices should be installed, or better grounding materials should be used.
	Nonfunctional	Preventative maintenance, frequent monitoring to make sure the system is operating properly, and troubleshooting, repairing, or replacing impacted components.
Mounting/Rack structure	Broken structure	To guarantee that the system is operating safely and effectively, immediate inspection, replacement, or repair of impacted components, preventative maintenance, system upgrades, and structural analysis are required.
Aerial cables	Excessive wear/ Overloading	Determine the extent of overloading or wear and tear on the aerial cables and determine the cause of the damage. The aerial cables for the solar PV system need to be constructed by the correct quality standards, and any damaged cables need to be repaired or replaced right away.
Inverter	Improper function	Examine the inverter to determine the severity of the issue, troubleshoot, reset, or reboot the device, repair or replace the inverter if needed, and maintain the system as a whole regularly.
	Degraded output	Determining the scope of the issue, diagnosing it, restarting or resetting the system, fixing or replacing the inverter as needed, and doing routine maintenance on the complete apparatus.
	Overloading	Find the cause of the overloading; electrical or wiring issues, excessive power consumption, load management strategies, proper ventilation and cooling, proper installation and wiring, regular maintenance, and system monitoring to ensure peak performance are all potential causes.
Earthing and grounding	Open or ineffective	Visually inspect the earthing and grounding system for signs of deterioration, corrosion, or wear. Make sure all of the connections are secure and tight. Make sure the installation is done correctly, perform regular maintenance, upgrade the grounding electrodes, replace or repair any broken parts, measure the earthing system's resistance with an earth tester, and adhere to safety protocols.
	Nonfunctional	Finding and fixing the root of the problem, changing or repairing broken parts, adjusting the earthing system, adding new parts as needed, carrying out routine maintenance, and putting safety procedures in place.
Mounting structure	Mechanical work failure/broken weld/ loosened bolts	Frequent inspection by user/Repairing of damaged part.
Connectors/Cables/ SPD (surge protection device)/MCB (Miniature Circuit Breaker)/Burnt fuse/ MC4 connectors/ Junction box	Burnt cables and fuse/SPD and MCB issue	Frequent visual inspection by user and expert/Replacing of damaged part.

Table 10. Life cycle cost of solar PV system.

Sr. No.	Cost component	Cost (INR)	% of LCC
1	Initial cost	2,31,480	25.63
2	O&M cost	5,70,000	63.10
3	Failure cost	1,01,765	11.27
4	Salvage cost	Nil	–
5	Life cycle cost	9,03,245	100

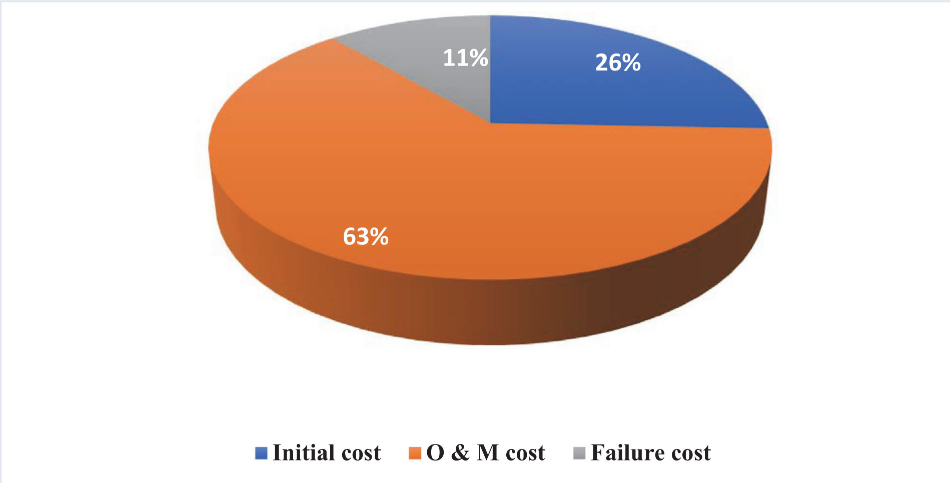

Fig. 6. Solar PV system life cycle cost breakdown.

According to LCC, the system's original cost accounts for 26% of the overall LCC, but the costs of operation maintenance and failure account for around 74% of the total LCC, making them the dominant factors. This fact emphasizes how crucial it is to run and maintain the plant properly. The O&M costs of the LCC account for over half of the total LCC, as illustrated in Figure 6. The PV system's total LCC includes the following:

- Initial Cost (26%) – This includes labor, installation, inverters, and solar panels.
- Operating & Maintenance Cost (63%) – This includes manpower, panel cleaning, and inspections.
- Failure Cost (11%) – Minor repairs and inverter replacement.

Therefore, by paying close attention to O&M costs, the solar PV plant's LCC can be maximized. It gives the user the idea that manual cleaning can cover O&M costs related to cleaning a panel in-house for small solar PV systems like those studied in this system. As the failure cost is less than that of O&M, periodic visits by technicians for regular inspection may be planned to reduce this cost. As described in Table 9, visual inspection by the user is recommended to avoid failure and to reduce inspection costs. Different maintenance solutions can be evaluated using this analysis.

Material extraction, manufacturing, and shipping all have an impact on the environment when PV components are maintained and replaced. This effect can be minimized by recycling programs and using inverters and panels for second-life use.

8 Conclusions

The exponential growth and extension of the Renewable Energy (RE) sectors, which include solar and wind, has made a clear and comprehensive evaluation of the economic feasibility of these technologies necessary. This worries the investors, developers, and decision-makers involved in the project. From the feasibility stage to the project completion and safe disposal stages, the costs of all the work required for these projects must be taken into account. Thus, LCC is a viable technique and strategy in light of global warming, especially for the RE system, which demonstrates the benefits of using RE as an alternative source in comparison to fuel-incurred costs (due to fluctuations) in the current context. An LCC model for a solar PV generation system has been built for an Indian setting using data and information obtained from developers, investors, and industry experts via a comprehensive questionnaire.

This paper presents a case study describing the LCC optimization of solar PV systems. The analysis results show that the components, such as the inverter, are critical from a LCC analysis perspective. Earthing and grounding, DC CB, IGBT, AC CB, Grid, AC converter, relay, inverter, cooling fan, and SMBUS communication component show less MTBF. So, these components' failure frequency is low, while the other components require minor repairs, which can be taken care of at O&M cost. Inverter replacement and failure costs can lead to high-cost investments, making them critical components contributing to almost 30% of total costs. This becomes very high comprise on cost.

Maximizing the LCC of a solar PV system by paying close attention to O&M costs is possible. The user is given the impression that O&M costs associated with manual panel cleaning might be incurred internally for small solar PV systems, such as the one under study in this system. Since the cost of failure is lower than that of O&M, scheduling an ideal technician visit for routine inspection can help save this expense. Table 9 explains that visual inspection by the user is advised to prevent failure and lower inspection costs. For projects with a life cycle of roughly 25 years, though the payback period is often less than eight years, if O&M is not taken care of, then it may cause high total LCCs.

There are a number of tactics that can be used to improve PV systems' efficiency and affordability. By enabling preemptive interventions, predictive maintenance with IoT-based sensors reduces maintenance costs and unexpected breakdowns through real-time monitoring. Optimizing panel cleaning using robotic or automated methods ensures greater efficiency without sacrificing environmental resources by lowering labor dependency and water use. System dependability is increased and failure costs are reduced by giving priority to long-lasting, high-efficiency inverters. Recycling and reusing PV components are examples of circular economy techniques that reduce lifecycle costs and advance sustainability. Lastly, by storing extra electricity, lowering grid dependency, and guaranteeing long-term cost savings, incorporating Battery Energy Storage Systems (BESS) optimizes energy consumption. When taken as a whole, these actions enhance system performance, lower operating expenses, and support environmental sustainability.

This study may not adequately represent the long-term degrading impacts of PV modules because it is based on operational data across 3–5 years. Findings may not be immediately applicable to extreme climate conditions like deserts or cold regions because the data was gathered from locations with a composite climate in India. Due to a lack of information on the recycling and resale markets, the salvage value of PV components at the end of their useful lives was not thoroughly examined. Variations in labor costs and automation (*e.g.*, robotic cleaning) were not considered; the study assumes fixed panel cleaning and inspection costs.

9 Future scope

Understanding the impacts of deterioration requires long-term performance monitoring of solar PV systems. IoT-based sensor real-time monitoring studies help improve predictive maintenance modeling. A circular economy strategy can improve sustainability even further. Effective end-of-life strategies for PV components can be developed with the use of LCC studies that take recycling benefits and costs into account. More effective use of resources may result from investigating the viability of repurposing old solar panels and inverters. By addressing these issues, solar PV systems will become more sustainable over the long run and more economically viable.

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