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Advancements in Failure Analysis Techniques for Concentrated Solar Power Systems

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Abstract. The reliability of Concentrated Solar Power (CSP) systems is important for continuous energy production due to the extreme environmental and operational conditions they work under. This paper offers a mini review of the latest advancements in failure analysis methods for CSP systems. This paper investigates the main causes of failure that threaten the efficiency and durability of CSP components, such as optical degradation, thermal stress, and fluid degradation. The review highlights important progress in diagnostic and monitoring methods such as thermographic imaging, reflectivity measurement, and fluid characterization, which are essential to identify and prevent these failures. Moreover, this review explores and discuss the use of predictive modelling for proactive maintenance and real-time monitoring of CSP systems. These advancements do not enhance only the predictive maintenance capabilities but also allow to improve the efficiency and durability of CSP plants.

Keywords: Failure Analysis, Concentrated Solar Power, Durability, Maintenance

1. Introduction

The principle of CSP technology is based on the capture of solar rays by mirrors which concentrate it onto a small surface, generating heat which is then transformed into electricity, making them an innovative technology of renewable energy. Nevertheless, this technology works under severe environmental conditions pose significant challenges. These challenges are worsened by stringent demands for high reliability and efficiency. Significant costs may occur if a critical component in a CSP system fails, leading to downtime, reduced energy production, and potential expensive repairs or replacements. Therefore, the significance of utilizing advanced failure analysis methods cannot be overstated. Lately, the scientific community has been increasingly focusing on developing and enhancing failure analysis techniques used to the specific needs of CSP systems. Even though they are effective in certain cases, conventional failure analysis methods have not been able to completely address the challenges related to CSP components. Solar collectors, heat transfer fluids, and thermal energy storage systems, are subjected to different stresses that can accelerate deterioration and result in unanticipated failures. The aim of this mini review is to present a summary of the latest developments in failure analysis methods for CSP systems.

2. Solar components

In concentrated solar power systems, solar components play an important role in the technology by ensuring the capture, concentration, conversion and storage of solar energy. Each of these components is designed to perform specific functions under severe environmental and operational conditions.

2.1 Solar collectors

The main critical component of a CSP plant are solar collectors. These components use different technologies to capture and focus sunlight to produce thermal energy [1]. Parabolic trough collector (PTC) is a common design with curved mirrors directing sunlight onto a tube filled with Heat Transfer Fluid (HTF). This type of collectors reaches optical efficiencies of up to 75%. Like all CSP technologies, PTC requires precise alignment of mirrors and consistent maintenance to prevent decrease of its performance caused by dust and soiling. Linear Fresnel reflectors (LFRs) are another type using flat or curved mirrors arranged in rows to focus sunlight onto a fixed receiver. Although their optical efficiency is generally lower, typically is about 65%, due to shading and alignment losses, LFRs offer advantages in cost and maintenance, making them attractive for large-scale deployments in high-irradiance regions [2]. Solar Tower (ST) systems, also known as central receivers, utilize groups of heliostats to focus sunlight onto a central receiver at high temperatures, which are optimal for efficient power cycles. These systems can achieve very high operating temperatures, often up to 1,000°C and reach annual optical efficiencies in the range of 60 to 65%, comparable to other CSP technologies. However, they incur increased installation and maintenance costs due to their intricate design [3]. Parabolic dish collectors focus sunlight onto a central Stirling engine or micro-turbine, converting heat into mechanical energy directly without relying on a heat transfer fluid. This technology eliminates the requirement for cooling water and offers a compact, independent system layout. Every type of collector takes into account efficiency, cost, and complexity, demonstrating the different approaches in CSP technology.

2.2 Heat transfer fluids

HTFs are also critical parts for the efficiency and reliability of CSP systems regarding their role to transport thermal energy from the solar receiver to the power block or thermal energy storage units. The selection of a suitable HTF depends mainly on its operating temperature range, thermal stability, viscosity, vapor pressure and fire safety characteristics. While water and steam offer cost advantages, their low boiling points and corrosion risks limit their application. Molten salts enable higher operating temperatures (565°C) but pose freezing risks and higher system complexity. Synthetic oils, particularly Biphenyl/Diphenyl oxide (DPO) mixtures such as Therminol VP1, have been widely used in commercial parabolic trough plants [3]. They offer excellent heat transfer but suffer from a low boiling point (257°C) and high vapor pressure, which contribute to gas generation and heat losses. As an alternative, hydrogenated terphenyl-based fluids like Therminol 66 offer lower vapor pressure and better thermal stability up to 300°C. However, ageing tests reveal thermal cracking at 350°C, leading to reduced flash points and viscosity. Despite this, Therminol 66 remains promising due to its lower volatility and resistance to oxidation under inert conditions. Thus, optimizing HTF selection involves balancing thermal performance with operational reliability and degradation resistance.

2.3 Thermal energy storage (TES) systems

Thermal energy storage systems play a crucial role in CSP plants, allowing for uninterrupted power generation by storing extra thermal energy when the sun is shining and using it later when sunlight is not available. Molten salt systems and steam accumulators are two of the most common TES technologies. Molten salt systems use independent hot and cold tanks to transfer heat from the storage medium to the heat transfer fluid. These systems provide high effectiveness and long hours of storage but require careful management to avoid issues like freezing or overheating. Nevertheless, steam accumulators use compressed steam to store energy, providing fast response and effective medium-term storage. Their performance is limited by the reduction in pressure upon release, as well as the suboptimal balance between volume and energy. Phase-Change Materials (PCMs) are an alternative method of storing thermal energy that use transitions between solid and liquid states. Thermocline systems offer a more cost-effective option by using a single tank filled with solid filler material, such as sand, quartzite rocks or ceramic bricks, layered with a heat transfer fluid to maintain thermal stratification [4]. However, they may lose efficiency over time due to thermal mixing. Recent studies have indicated that optimizing the thermal energy storage size and solar multiple can have a significant impact on the levelized cost of energy (LCOE) and system performance [5-8]. This shows the significance of extensive planning and ongoing changes to improve effectiveness and financial viability.

3. Failure mechanisms and root causes

CSP systems operate under severe conditions characterized by extreme temperatures, high radiation levels, and environmental stresses that cause different failure mechanisms for solar components. Understanding these failure mechanisms and their root causes is essential for developing suitable strategies that allow decrease of risks and ensure their durability.

3.1 Optical degradation

Optical degradation is one of the most significant failure mechanisms in CSP systems, especially for solar collectors that depend on the precise reflection or concentration of sunlight. During the operating time, the optical performance of mirrors and lenses can deteriorate due to several factors [9,10]:

- Dust and soiling: Dust, dirt, and other particles can accumulate on the reflective surfaces of solar collectors, reducing their ability to concentrate sunlight effectively. In regions with high dust levels or frequent windstorms, soiling can lead to a significant loss in optical efficiency, potentially reducing energy output by 5-20%. Regular cleaning is necessary, but improper cleaning techniques or abrasive materials can cause scratches, further exacerbating optical losses.
- Weathering and environmental exposure: Exposure to harsh environmental conditions, such as Ultraviolet radiation (UV), humidity, and temperature fluctuations, can degrade the materials used in mirrors, lenses, and coatings. UV radiation can break down polymeric materials, causing yellowing, cracking, and loss of transparency. Moisture can lead to corrosion of metallic components, especially in coastal areas with high salinity, compromising the structural integrity and reflectivity of mirrors.
- Reflective coating degradation: The reflective coatings on mirrors, usually composed of silver or aluminum, are subjected to oxidation and corrosion during operating time. Even minor degradation of these coatings can result in significant optical losses, as the reflectivity decreases, reducing the amount of concentrated solar energy reaching the receiver. Protective coatings are applied to prevent oxidation, but these can also degrade under harsh conditions, necessitating regular reapplication.

3.2 Thermal stress and material fatigue

Thermal stress is a critical failure mechanism that affects various components in CSP systems, especially those exposed to repeated heating and cooling cycles, such as receiver tubes and mirrors:

- Thermal expansion and contraction: CSP components are subjected to continuous expansion and contraction because of the significant temperature variations between operation and downtime. Receiver tubes can reach temperatures of over 500°C during operation but may cool rapidly when the sun is obscured by clouds or at night. This fluctuation in temperature can result in mechanical stress, leading to cracks, warping, or deformation of materials over time [11].

- Material fatigue: Repeated thermal cycling induces material fatigue, a process where the material's microstructure is progressively damaged, causing the initiation and propagation of cracks. In metallic components, this can result in creep (slow, permanent deformation under constant stress) [12], eventually leading to failure. In glass components, such as mirrors or protective covers, thermal stress can cause microcracks that grow over time, reducing the component's strength and durability.
- Thermal shock: Sudden temperature changes, such as those caused by rapid weather changes or emergency shutdowns, can lead to thermal shock, where the material experiences a sudden and severe stress that exceeds its mechanical limits. This can cause immediate cracking or fracture in brittle materials like glass or ceramics used in CSP components [13].

3.3 Mechanical failures

Mechanical failures in CSP systems often involve the moving parts of the tracking systems, support structures, and other mechanical assemblies that must withstand constant motion, environmental loads, and wear:

- Wear and tear: Solar reflectors in CSP systems suffer from environmental abrasion and dust accumulation, leading to reduced reflectivity and efficiency [14]. Additionally, in falling particle-based systems, heat exchange surfaces experience erosion from high-temperature particles [15]. Over time, these factors contribute to the gradual degradation of critical components, impacting the overall performance of the CSP system.
- Structural deformation: CSP systems, especially solar towers and parabolic troughs, have large structures that must endure wind loads, thermal expansion, and mechanical stresses. Over time, these stresses can cause deformation of support structures, leading to misalignment of mirrors or heliostats, which in turn reduces optical efficiency [16]. In extreme cases, structural deformation can lead to catastrophic failure, such as the collapse of a heliostat tower or the buckling of a support frame.
- Corrosion: Corrosion is a pervasive issue in CSP systems, particularly affecting metallic components like solar reflectors [10] and alloys used in salts [17]. Exposure to moisture, salt, and other corrosive agents can weaken these components, reducing reflectivity, compromising mechanical integrity, and leading to failures in critical areas such as support structures and heat exchange surfaces.

3.4 Fluid degradation

Heat transfer fluids play a vital role in CSP systems by transporting thermal energy from the receiver to the power block or storage system. However, HTFs are susceptible to degradation due to high temperatures, oxidative environments, and prolonged use:

- Thermal decomposition: HTFs, particularly synthetic oils and organic fluids, are prone to thermal decomposition when exposed to high operating temperatures for extended periods [2,18]. This decomposition results in the formation of low-molecular-weight compounds, gases, and solids (e.g., coke), which can increase the viscosity of the fluid, reduce heat transfer efficiency, and cause fouling of heat exchangers and pipelines.
- Oxidation: In the presence of oxygen, HTFs can undergo oxidative degradation, forming acids and other reactive species that can corrode pipelines, valves, and other system components [18]. Oxidation is particularly problematic in systems with leaks or where the HTF is exposed to air, necessitating the use of inert gas blanketing or antioxidant additives to prolong fluid life.
- Contamination and phase separation: Contaminants such as water, dust or degradation products can enter the HTF, leading to phase separation, where the fluid no longer remains homogeneous [19]. This can cause blockages, reduce heat transfer efficiency, and lead to uneven heating, which in turn exacerbates thermal stress on components.

3.5 Thermal cycling effects in energy storage systems

Thermal energy storage systems are critical for CSP plants to deliver energy during non-sunny periods. However, these systems are susceptible to degradation due to thermal cycling:

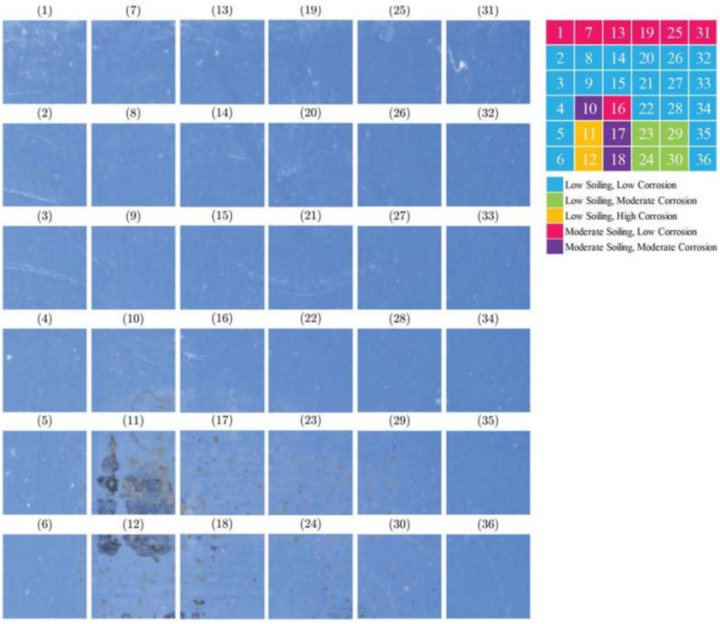
- Mechanical stress in storage media: TES systems, especially those using solid media like quartzite or phase-change materials, undergo repeated expansion and contraction during charge and discharge cycles [20]. This mechanical stress can cause cracking or disintegration of the storage media, reducing the storage capacity and efficiency over time.
- Thermocline degradation: In thermocline storage systems, the temperature gradient within the tank can degrade over time due to mixing and diffusion, leading to reduced stratification and lower storage efficiency [21]. This degradation is accelerated by thermal cycling and the inherent differences in thermal conductivity between the storage media and the fluid.
- Molten salt degradation: In two-tank molten salt systems, the high operating temperatures can lead to the formation of solid impurities, which can precipitate and cause blockages in the system [22]. Additionally, the molten salt can become contaminated with water or other impurities, leading to a reduction in thermal capacity and potential corrosion of storage tanks and pipes.

4. Advancements in diagnostic techniques and monitoring

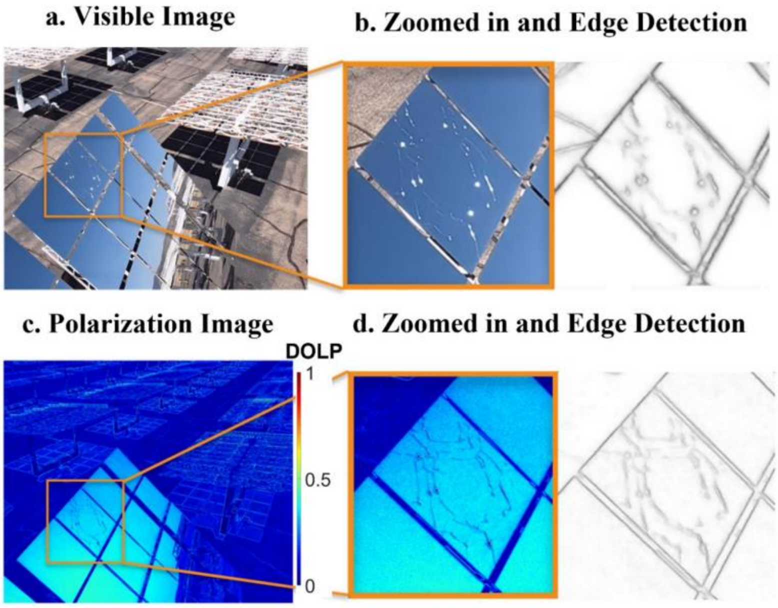
As the complexity and scale of CSP systems increase, so does the need for sophisticated diagnostic and monitoring techniques to ensure their reliability and efficiency. Recent advancements in these areas have led to the development of cutting-edge tools and methodologies that allow for real-time monitoring, early detection of potential failures, and proactive maintenance.

4.1 Acquisition and thermographic imaging

New imaging technologies have significantly advanced the early detection of failures in CSP systems. Aerial image acquisition using drones is increasingly employed to monitor heliostat mirrors and assess soiling levels (Figure 1) [23,24]. Despite challenges such as GPS drift, heat interference, and large-scale data processing, the use of random waypoint methods and dedicated pipelines for mirror segmentation and reflectance estimation has achieved promising accuracy levels of 2–3%, with ongoing efforts to improve it below 1%. This technique enables more reliable and automated heliostat monitoring. Thermographic imaging, or infrared thermography, is another essential tool for diagnosing thermal anomalies in CSP systems. This non-invasive method uses infrared cameras to capture temperature distributions across key components such as solar collectors and receiver tubes. It excels in detecting hot spots by identifying areas with abnormal temperatures, which can reveal issues like misalignment, fouling or material degradation. This early detection allows for targeted maintenance and prevents larger problems. Additionally, thermography assesses heat transfer efficiency by analyzing temperature gradients along receiver tubes and in thermal energy storage tanks, helping to identify blockages or insulation failures. Advances in drone technology have enhanced thermographic imaging by enabling remote and automated monitoring of expansive solar power fields [25]. Drones equipped with infrared cameras can quickly scan large areas, providing real-time, high-resolution thermal images that improve inspection speed and accuracy, thus supporting more effective maintenance and operational management.



(a)



(b)

Figure 1. *(a) Experimental mirror segment divided into a 6 x 6 cells grid, highlighting the state of each cell [24]. b) Example crack detection using a polarimetric imaging drone for inspection of heliostats on the CSP Sandia NSTTF field [23].*

4.2 Reflectivity measurement

Reflectivity measurement is crucial for maintaining the efficiency of CSP systems. Advanced techniques enable precise assessment of the reflective surfaces of solar collectors. Spectrophotometry measures the reflectance spectrum of mirrors across different wavelengths, helping to detect degradation from UV exposure, dirt, or physical damage [26]. This technique is essential for monitoring long-term mirror performance and determining when recoating or replacement is necessary. Portable reflectometers provide on-site, immediate feedback on mirror condition, allowing for quick decisions on cleaning or maintenance. Their ease of use and portability make them valuable for routine inspections. Laser scanning systems offer high-precision mapping of solar collector surfaces, detecting deviations from the ideal mirror shape

[27]. In particular, they allow for the quantification of geometric errors such as contour deviations, canting misalignments, and surface roughness. Surface roughness—or micro-scale irregularities—can increase light scattering, thereby reducing the optical efficiency of the collector even when its macro-geometry appears intact. Publication [27] presents a comprehensive methodology using laser scanning and image processing to characterize these defects through canonical image representations, enabling the calculation of energy-relevant parameters such as the interception index and the energy concentration index. This approach is particularly effective for identifying the cumulative impact of geometric distortions and micro-roughness on energy capture under real operating conditions.

4.3 Fluid characterization and monitoring

Fluid characterization and monitoring are essential for maintaining the performance of CSP systems, as HTFs and working fluids are critical to system operation. Advanced analytical methods, including gas chromatography, mass spectrometry, and Fourier-transform infrared spectroscopy (FTIR), are increasingly utilized to analyze the chemical composition of HTFs. These techniques can detect degradation products, contaminants, and changes in the fluid's chemical structure, which may impact its thermal properties and lead to inefficiencies or failures in the system. Real-time monitoring of HTF properties is facilitated by advanced sensors that measure viscosity and thermal conductivity. Installed in the fluid circuit, these sensors provide continuous data on the fluid's condition, enabling early detection of issues like thermal degradation or phase separation. Additionally, inline corrosion sensors are employed to monitor corrosive wear in pipes and components in contact with HTFs. By measuring parameters such as pH, Oxidation-Reduction Potential (ORP) and corrosion rates, these sensors help prevent unexpected failures and extend the lifespan of system components, ensuring reliable CSP system operation.

4.4 Condition monitoring systems

Condition monitoring systems have evolved to provide comprehensive, real-time data on the health of CSP components, facilitating predictive maintenance strategies. Vibration analysis is a key component of these systems. Vibration sensors installed on rotating equipment, such as pumps and motors, can detect imbalances, misalignments, and bearing wear. By analyzing vibration patterns, these systems can predict mechanical failures before they occur, allowing for timely maintenance interventions. Acoustic emission testing complements vibration analysis by monitoring high-frequency sounds emitted by materials under stress. Acoustic emission sensors can detect early signs of crack formation or structural defects in components like receiver tubes or support structures [28]. This early detection enables proactive maintenance, preventing catastrophic failures and extending the lifespan of critical components. Fiber optic sensing is another advanced technique increasingly used in CSP systems. These sensors are embedded within or attached to critical components, providing continuous data on temperature changes, thermal expansion, and mechanical strain. The high sensitivity and accuracy of fiber optic sensors make them ideal for monitoring large-scale CSP installations.

4.5 Predictive modeling and simulation

The integration of predictive modeling and simulation into CSP system management represents a significant advancement, enabling operators to anticipate potential failures and enhance system performance. Computational Fluid Dynamics (CFD) is a crucial tool in this area. CFD simulations model fluid flow, heat transfer and thermal cycling within CSP systems [29]. By simulating various operating conditions, CFD models predict how HTFs behave under different scenarios (Figure 2). This capability helps optimize the design of components such as receivers, heat exchangers and storage tanks, ensuring better system performance and efficiency. Finite Element Modeling (FEM) is also employed to assess structural integrity under thermal and mechanical loads, enabling accurate predictions of deformation, fatigue and stress concentrations in critical CSP components.

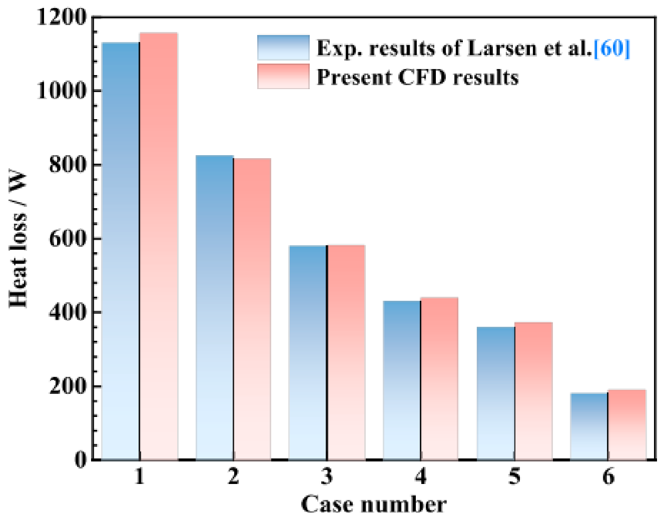


Figure 2. *Example of a computational fluid dynamics model used to obtain the optical thermal performance of a collector under various operational conditions. The graph shows a comparison between the predicted heat losses of the receiver and the test results reported by Larsen et al. [29].*

This is essential for understanding failure mechanisms induced by cyclic temperature variations. In terms of optical performance, Monte Carlo Ray Tracing (MCRT) simulations offer a powerful approach to model light reflection, absorption and scattering within the solar field. When combined with CFD and Artificial Neural Networks (ANN), this hybrid MCRT-CFD-ANN approach enables both real-time and annual evaluations of collector performance with high predictive accuracy ($R^2 > 0.9999$), as demonstrated in recent research [30]. This multi-scale model captures efficiency variations throughout the year and offers strategic guidance for performance optimization. In addition, advanced thermodynamic modeling is employed to simulate the overall performance of CSP plants. These models evaluate power output, efficiency, and thermal losses, incorporating real-time data from monitoring systems to provide dynamic predictions. This allows operators to adjust operating parameters to maximize efficiency and reduce component wear. Soiling prediction models based on neural networks have also been developed to estimate the impact of environmental conditions, such as dust deposition, humidity and temperature, on the optical degradation of mirrors (Figure 3). For example, publication [31] shows that ANN models trained on weather and pollution data can effectively predict reflectance loss, corrosion and paint yellowing in solar reflectors exposed to Moroccan desert and coastal environments. Such models support site-specific maintenance planning and enhance optical reliability over time.

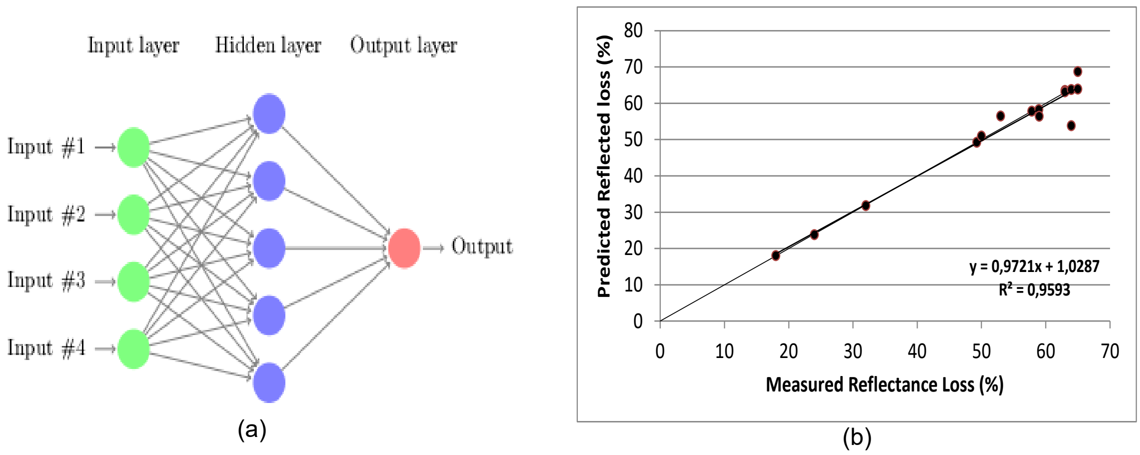


Figure 3. *Neural network structure (a) and training results for specular reflectance loss (b) due to dust deposition on mirrors exposed at a seaside site in Morocco [31].*

The concept of digital twins further enhances predictive capabilities. A digital twin is a virtual replica of a physical CSP system, created using real-time data, historical performance data, and predictive models. Analyzing the digital twin allows operators to foresee potential issues, schedule maintenance more effectively, and optimize system operations for improved performance and longevity, bridging the gap between theoretical models and actual system behavior.

5. Conclusion

The advancements in failure analysis techniques for CSP systems represent a significant leap forward in enhancing the reliability and efficiency of this vital renewable energy technology. As CSP systems operate under challenging conditions, addressing failure mechanisms such as optical degradation, thermal stress, and material fatigue is crucial for maintaining optimal performance. Recent progress in diagnostic tools and monitoring technologies—including thermographic imaging, reflectivity measurements, and advanced fluid characterization—has markedly improved our ability to detect and address potential issues early. The integration of these technologies with real-time data analytics, machine learning, and IoT-enabled sensors provides a robust framework for proactive maintenance and operational optimization. These advancements not only extend the lifespan of CSP components but also bolster the economic and environmental benefits of solar power. Continued innovation in predictive modeling and material durability will be essential to overcoming remaining challenges and securing CSP's role as a cornerstone of sustainable energy.

Data availability statement

Data will be made available on request.

Author contributions

Please include a statement on authors' contributions according to the CreDIT guidelines here. CRediT (Contributor Roles Taxonomy)’s intention is to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Competing interests

The authors declare that they have no competing interests.

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