Degradation Science from Nanometers to Kilometers: A Pathway to Rapid Detection for Reliable Photovoltaics

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Photovoltaics reliability for terrestrial applications has more than four decades of history and experience. International standards development has prevented many early life failures and must be continued in the future. Yet, as the module product development cycle is measured in mere months, additional investment in the fundamental degradation science and rapid detection should be developed. In this article, a brief strategy is provided addressing indoor accelerated, outdoor testing, and modeling efforts required to retain high reliability in the following decade.

1. Introduction

When the National Renewable Energy Laboratory (NREL)—originally known as Solar Energy Research Institute (SERI)—was founded in 1977 the directive was to drastically reduce cost of photovoltaics (PV) because as a novelty for terrestrial application the cost exceeded several hundred US \$ per Watt. Cost reduction and efficiency gains have since been primary drivers to move PV from a novelty to a broad worldwide market. The deployment is expected to grow even more rapidly to mitigate the effects of climate change. The industry has obviously matured, yet underperformances caused by degradation phenomena at the cell, module, and systems level have the potential to derail PV's remarkable success story.

Understanding failure mechanisms can help to improve future products, for PV as for other technologies. Failures in PV, often defined as a 20% loss from initial performance (when defined at all), can occur through the sudden loss in performance or through the gradual loss during months and years. Warranties have used many definitions for failure over the last 45 years, but many also use 20% performance loss before the projected end of module life. Catastrophic performance loss is not commonly observed without a triggering event,[1] although severe defects creating safety issues have occurred. Gradual power loss through degradation can lead to substantial underperformance and financial losses. Some of the authors have found that commercial and utility systems lose performance at an annual rate of 0.75% at the median in the USA, similar to findings for systems in Europe.[2,3] Other studies have found higher-performance losses in other geographical regions or different fleets.[4–7]

Decarbonizing the US and global electrical grids will require unprecedented scale up in the manufacturing and deployment of PV. One conservative estimate for the US, the Solar Futures Study, has developed several scenarios requiring circa 1 TW of PV in the USA alone by 2035 to decarbonize the electrical grid.[8] Considering that the USA had a cumulative installed capacity at the end of the third quarter in 2022 of ≈130 GW, targeting 1 TW will present a substantial challenge.[9] If we could reduce the performance loss from a median of 0.75% year^{-1} to 0.50% year^{-1}, the savings would be several US \$ billion (see Appendix). It would also reduce yearly decommissioning, replacement, and recycling demand by 2.5 GW PV module capacity covering approximately 30 km^2 every year using current land requirements.[10] The challenge to reduce long-term degradation by a quarter percent per year may be an equally daunting challenge that the SERI pioneers must have felt for reducing cost in 1977. Yet, as they might not have envisioned the dramatic changes, we have witnessed in the last four decades, with investment in foundational science, we may overcome this challenge.

2. The PV Reliability Learning Cycle

PV has a decades-long history of quality improvement and testing that originated in the late 1970s and early 1980s. In the USA, the Flat-Plate Solar Array project, colloquially known as the Jet Propulsion Laboratory Block Buy Program, initiated during that time. During this program, PV modules from manufacturers at the time underwent accelerated testing and outdoor exposure. Failures were observed, and in a continuous improvement process, feedback to the manufacturers was provided. Through 5 rounds—so-called block buys—the products were steadily improved with the lifetime of PV modules increasing from less than a year to more than 10 years. The close collaboration between manufacturers and test laboratories was exemplary and had no small part in the success of the program. Subsequently, many of the developed tests along with a simultaneous effort from the Commission of European Communities Specification 500–503 were incorporated into the International

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Electrotechnical Commission (IEC) 61215 PV module qualification standard. The number of tests in the standard have proven to be very adept in detecting module design issues that would have led to early life failures. Yet, it is important to understand the purpose and limitations of this and other standards. Because of the evolving technology, the standard is continuously adapted to new observations and technologies. However, it can take years from initial field observations of failures over test development to incorporation into international standards. During this time, many designs or materials combinations—documented in the bill-of-materials (BOM)—may enter the commercial market undetected.

It is also important to understand that the module qualification standard does not attempt to provide information on lifetime. Arbitrarily extending tests from IEC 61215 may activate failure modes never encountered during field operation, a typical pitfall of accelerated testing and must be avoided. Extended stress testing currently under development and published as technical specification IEC TS 63209 will help, but the absence of lifetime prediction may impede future PV deployment. It is imperative that these standards are continued to be developed and adapted to field observations to protect the industry and power system from catastrophic early failures. One example of this is in newer "retest" requirements, which stipulate which BOM changes trigger new qualification testing of a module. These requirements should reduce those undetected BOM changes, but they do not address the potential changes to lifetime. Because today new products typically enter the market every few months and cost and supply chain consideration may lead to a diverse number of BOMs even in the same module type that can render lifetime prediction daunting.[11]

The challenge may seem formidable, but the reality is the PV community has more than four decades of experience in PV reliability to draw from and a history of research on molecular/microscopic changes that occur with excessive module degradation. Rapid detection of some problems will require more research, yet is attainable. The situation is also urgent, as illustrated in a simple example. Assuming that a large module manufacturer may produce multiple GW/year manufacturing of a new module design using novel materials, a single-gigawatt module factory may be producing hundreds of modules in several parallel manufacturing lines per hour. One of the crucial module qualification tests, exposure to damp heat (85 °C and 85% relative humidity) lasts 1000 h and degradation is assessed post exposure. Hypothetically, if the damp heat were to reveal an early failure sign during that same time period, potentially hundreds of thousands of modules with the same flaw may be produced in that single-gigawatt factory and enter the market. In reality, module qualification on a new design takes place in parallel to manufacturing of older proven designs. However, without early, rapid detection, the risk of a catastrophic flaw entering the commercial market on a large scale does exist. Therefore, how can we prevent this scenario when current accelerated tests are designed to detect known failures in familiar materials take months to carry out? Naturally we may not be able to have early detection of all problems, particularly with new types of failure mechanisms, but rapid detection of chemical/molecular instability, physical stress, or even some well-known failure modes that reappear periodically could save millions of dollars, time, and reducing waste.

In the following sections, we lay out a roadmap that may not directly lead to lifetime prediction but in all cases may be a necessary first step in that direction.

3. Enhanced Indoor-Accelerated Testing

Degradation and failure can be separated into "recoverable" and "non-recoverable" losses. Recoverable losses are related to availability issues that can be repaired through a combination of monitoring and operations and maintenance (O&M) best practices. Inverter that converts the direct current (DC) from PV modules to alternating current (AC) is the system component often associated with the most O&M tickets.[12] Another example may be trackers that are designed to follow the sun's path to maximize production but lead to lost production when they stop tracking. At the module level, soiling can cause severe underperformance depending on the geographical location that can be recovered through cleaning. Although, soiling can also lead to non-recoverable losses when the particles lead to abrasion or become ingrained in the glass of the module itself. Despite the existence of a gray area, we focus here on the non-recoverable part of degradation. Degradation and failure are naturally related for components and systems as they degrade and fail along a hazard rate curve that is often described colloquially by a "bathtub curve" because of its increased failure rate early and toward the end of its useful life. However, for PV modules, the curve is less symmetrical with a lower failure rate in early life due to the successful development of IEC and other standard qualification tests.[13]

PV modules require robust and durable packaging to survive harsh climate and mounting configurations. While this packaging is necessary for practical use, it also impedes the easy characterization and understanding of degradation mechanisms. The situation may be somewhat reminiscent of Plato's cave allegory where shadows in a cave are observed, and the "real world" events are inferred from the shadows on the wall. And, while many characterization methods are available, each of which provides valuable information, understanding the underlying physical and chemical mechanisms is still difficult and may take considerable effort and time. Modules are often viewed as a single entity, as they are sold this way, yet they should be really understood as multifaceted systems where multiple thermal, chemical, electrical, and optical degradation mechanisms may take place simultaneously and may lead to complex interactions.

The PV community has become proficient in the last 45 years developing meaningful tests and methods, physical characterization, and modeling approaches, that greatly contributed to our understanding of the physical and chemical processes taking place inside PV modules. The situation is illustrated in a few examples in **Figure 1**. In today's graphic on the left, the outer ring contains a number of techniques used today to characterize degraded module, from indoor accelerated tests or from field installations. Yet, they are lagging degradation indicators because they only detect changes after significant optical alterations or performance loss. The upper left quadrant illustrates in a simplified picture cell cracking, one of the biggest current concerns in the industry. Cracked cells can, but do not always, lead to hot

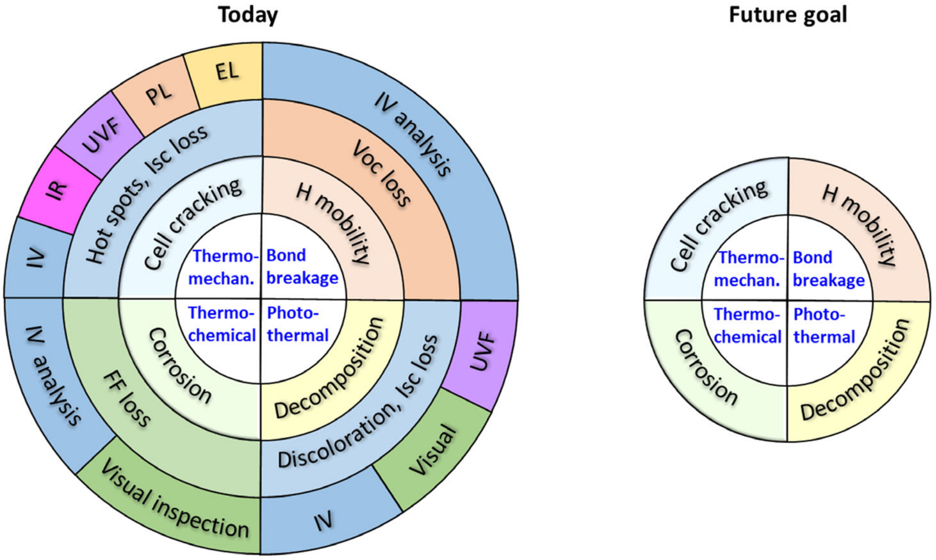

Figure 1. Connection illustration of external characterization techniques, degradation modes or symptoms, degradation mechanisms, and the driving physical or chemical phenomena on the interior for a few examples.

spots that can be readily detected in infrared (IR) characterization. Each of the other methods, electroluminescence (EL), photoluminescence, and UV fluorescence (UVF), can visualize cracked cells in a module. Although, the details on how these cracks lead to power loss eventually are still being investigated. The mechanism is shown in the second-innermost circle and may be understood through physical and chemical driving phenomena in the center of the circle.

The lower left quadrant illustrates the case of corrosion that may be detected by visual inspection or through current–voltage (IV) measurements. Encapsulant discoloration in the lower right quadrant, historically one of the most commonly observed degradation modes or symptoms, is caused by the photothermal decomposition of the encapsulant. Lastly, the upper right quadrant illustrates a mechanism observed in some high-efficiency modern modules where hydrogen (H) may be used to passivate defects and/or dangling bonds. These detailed studies at the atomic scale frequently can be only accessed through destructive characterization.[14] This type of reverse engineering is very useful, as it makes a range of indoor surface and interface characterization tools available. Yet, these detailed characterization methods frequently take considerable time. Often by the time the causes of the degradation are established, the product under investigation is no longer sold. This rapid technological development is the reason to focus on the underlying mechanisms and not the observed modes such that the learnings can be more easily transported to updated products. For some mechanisms, full-sized modules are not required; instead, coupon or mini-module testing in combination with modeling can provide the same insights greatly accelerating understanding, although it may not be applicable for all mechanisms.[15] Laminated mini-modules or quarter modules have many of the built in stresses and degradation drivers (interface delamination, voltage, photochemistry, thermomechanical stress, ionic/electron diffusion, etc.) as full-size modules, but they may allow higher testing throughput or testing “in-operando” to allow real-time microscopic or spectroscopic observation of degradation.

To turn away from Plato’s cave shadows toward the real events, it would be extremely useful to observe degradation mechanisms directly instead of relying on indirect methods or destructive characterization. This is especially important because failure mechanisms may be multistep processes that can be missed by conventional accelerated tests. One example of a multistep/multi-stress failure mechanism that was missed by standard testing is a type of triple-layer polyamide backsheet that was introduced by module manufacturers around 2010 due to cost and supply chain constraints. Five to 10 years later, almost all these backsheets had failed and modules needed to be replaced despite passing the module qualification test at that time.[16] The reason is that the failure mechanism required a combination of mechanical stress and temperature cycling, and traditional tests on modules and coupons did not provide the combination as it occurred in the field. Newer tests on laminated coupons or combined accelerated testing (CAST) today can reveal this type of failure.[17] However, CAST today is done at the macroscopic level. Being able to induce multiple stresses in situ while observing microscopic or spectroscopic changes could provide valuable insight into the degradation of materials and interfaces.

Today, some indoor tests such as damp heat are fairly long tests because there are fundamental limits on how much stress (e.g., temperature, voltage, pressure) can be increased or accelerated without producing results that would never be seen in the field. Directly observing microscopic changes under low-acceleration factors of combined stresses as they occur in the field could speed up the learning cycle and detect weaknesses in new materials/combinations. **Figure 2** captures a situation where a cell is exposed to multiple stressors such as relative humidity, temperature, and UV exposure while being characterized in situ. New tools may be required for this emerging application. Atmospheric SEM has been developed and could

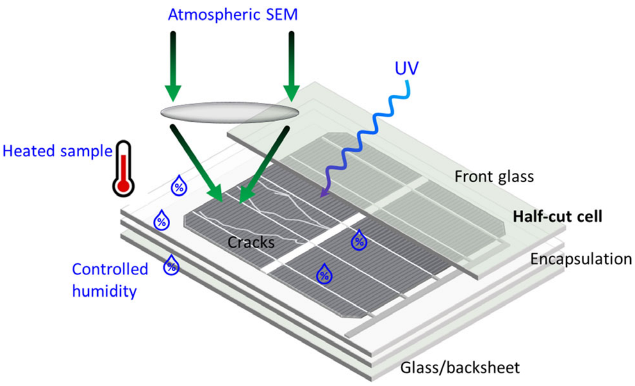

Figure 2. Illustration of an in situ degradation characterization tool on a 1 cell minimodule. Today, reliability testing is typically done on fully packaged modules making it difficult to detect physical and chemical changes in real time. Atmospheric scanning electron microscopy (SEM) may be a tool used to detect changes at the molecular or atomic level while simultaneously exposing samples to environmental stresses such as temperature, humidity, and ultraviolet radiation.

see some application in this field[18] along with operando spectroscopy. Combinations of different BOMs could be quickly tested and screened for incompatible combinations.

4. Rapid-Field Monitoring and Detection

Multimodal analytic analysis can help in the detection of early signs of degradation. Many commercial or large system owners now have regular system health checks including EL, IV, and IR imaging. Combining these data with the streaming time-series performance data may enable us to identify serious degradation issues earlier and plan mitigation before those systems fail or lead to substantial financial losses. These discrete methods provide valuable information on the operating modus of the plant but are similar to the current indoor tests time consuming and focused on the symptoms. Analytical methods may be the key to extracting additional knowledge from data that is already collected and accelerating the PV learning cycle. Large PV installations are typically equipped with their own or multiple weather station depending on the size of the installation, which may consist of temperature, irradiance, and wind measurements. Depending on the type of installation and mounting other data streams may include tracker angle for systems that follow the path of the sun to maximize production. Yet, the increased functionality and decreased size of smart sensor technology have not entered mainstream PV installations at a large scale. In contrast, state-of-the-art cell phones that are almost ubiquitously carried by the majority of people across the world may contain as many as 14 smart sensors. Deploying more sensors in PV systems in addition to the common weather instruments could have multiple benefits. Much could be learned with a more widespread utilization of sensor technologies in terms of degradation science, and the collected data could simultaneously serve as red-flag warning systems of early onset degradation. Today, early detection is focused on short-term effects such as full, partial outages or gross underperformance, although the more subtle of early degradation signs are often not noticed for years. Therefore, being able to detect early signs within months would be a tremendous improvement and could have a substantial impact on the industry.

Smart instrumentation in the form of multiple sensors could provide high-resolution spatial and temporal data and made "smart" in combination with automatic detection algorithms. **Figure 3** provides an example of the deployment of the use of sensors in a commercial installation. The displacement of the modules is shown on a windy and calm day. The displacement increases during the day in both cases because the modules are mounted on a tracker, but the difference between the two days in the small displacements is striking. This is particularly important because of the increased frequency and intensity of extreme weather events such as high wind and hail.[19] Hail events can lead to broken front glass in modules where the damage is obvious. However, because of decreased front glass and cell thickness damage to the interior of the modules may occur yet not be invisible to the naked eye. Sensors such as shown in Figure 3 may

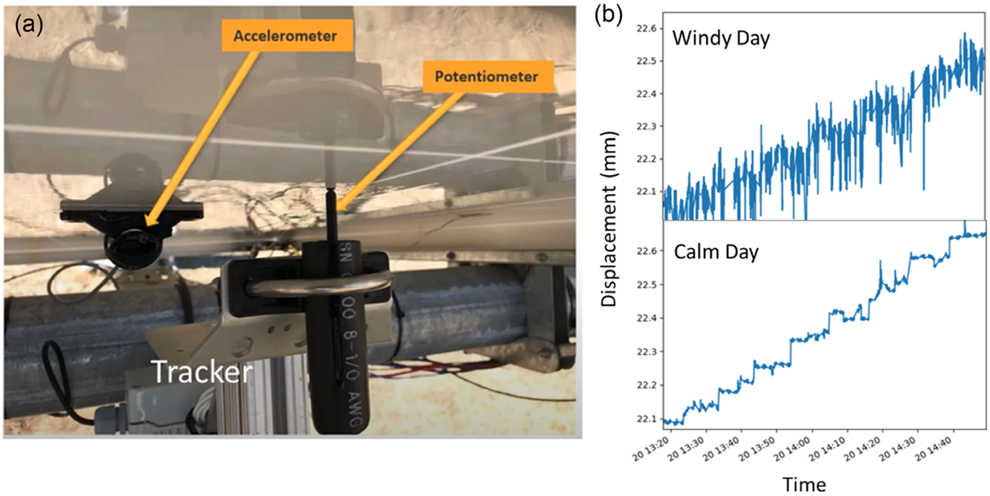

Figure 3. a) Example of photovoltaics (PV) module sensor attachment and b) example data on a windy and calm day. The displacement increases in steps because of the motion of the 1-axis tracker.

indicate the extreme weather event and alert operators to target the system for early inspection and maintenance. A non-exhausting list may include acceleration and impact sensors may be complemented by strain gages to measure bending and torsion; displacement and high-frequency measurements on the PV modules and structures to detect system health and early onset of degradation. Data analytical methods, especially machine-learning algorithms, would be a crucial method in developing these early degradation onset tools. Performance data on commercial and utility systems is usually collected in 15 min increments.[2] Higher-frequency data may be needed but could provide more accurate insights into the health of systems.

Early detection is also important because more systems are installed in geographic locations more prone to extreme weather increasing the probability of damage that has to be mitigated as soon as possible. In addition to a wider geographic location, new application in PV such as the combination of PV and agriculture or installation of PV on water surfaces could potentially impact long-term reliability. Agrivoltaics—the combination of agriculture and PV—can diversify the revenue stream of farmers in addition to other benefits such as increased crop yield reduced water usage, etc.[20] Reliability consequences, if any, are not understood yet, although PV systems for agriculture may be installed at greater height, potentially making them potentially more susceptible to higher wind speeds. PV systems near agricultural sites also tend to exhibit more soiling. Installation of PV systems on water surfaces—floating PV—has great potential especially in areas of high land cost. Mutual financial and ecological benefits include increased production because of evaporative cooling and reduction of algae growth.[21] Floating PV modules are exposed to slightly higher humidity and lower temperatures than ground-mounted systems, and mechanical loads due to wave motion and wind are different. Nonetheless, the reliability challenges to have high current in such close proximity to a body of water seem obvious but can be solved with proper engineering methods.

5. Developing Predictive Models

Developing predictive models requires the understanding and modeling the underlying causes. Some success with specific models has been attained but they often target a specific single-step mechanism, material, or interface.[22,23] Standard and extended accelerated testing can predict if some known failures are likely to happen, but not when or how they will impact power loss. As mentioned earlier, encapsulant browning is something we can easily screen for, but it doesn't have a substantial effect on power production. The new backsheet coupon test and combined accelerated stress testing can accurately predict which materials are likely to fail under field conditions, but not the rate or timing. The community can screen for potential weaknesses well, but it will be extremely difficult to predict future degradation or performance without a combination of modeling, accelerated testing, and outdoor performance data. High-quality models are required to correlate observations from test samples to full-size modules and to extrapolate observed degradation rates and mechanisms to longer times or actual outdoor conditions. PV technology changes too quickly for a purely fundamental or "bottoms up" analytical modeling approach to be developed for every variation of BOM. However, this rapid growth also provides tremendous quantities of testing and field performance data enabling a more data-driven approach. A hybrid modeling approach, a mixture of bottoms-up modeling using fundamental physical and chemical process in conjunction with top-down data-driven approach may be key.

Many degradation mechanisms are multistep processes, requiring an initiation step, some probability, and rate of propagation, followed by the eventual failure. These processes need to be described by a combination of rate equations and probabilistic statistics. Modeling can become very complex when several of these multistep degradation phenomena are combined together to describe a module installed outdoors for many years. Building these hybrid models with multiple stresses, interfaces, and probabilities of failure is essential if we want to predict the routine degradation rate of modules under normal operation and the onset of "wear-out" or end of life. Wear out occurs when multiple degradation mechanisms synergistically accelerate to failure. Validating these models is also going to be difficult, and some validation will have to be done based on accelerated testing and limited outdoor performance data. We will also need to rethink some of testing protocols. The existing standards use testing in sequences that typically provoke known failures in poor materials and designs. New testing may have to carefully consider different initial conditions, propagation conditions, failure criteria, and mitigation options.

The DuraMAT consortium in the USA focuses on solutions to PV module materials durability questions. It had some success in scaling relationships and is investing heavily in experimentally validated predictive modeling capabilities. Recently, it has proposed a framework for hybrid modeling using modeling chains.[24] The modeling chains allow us to apply the models more broadly and most importantly take into account synergistic effects between different mechanisms. Building these chains up to model the real-time degradation of different types of modules will take a concerted collaborative effort between institutions all over the world. Some will focus on fundamental models for physical and chemical processes, others will focus on probabilistic failure models based on different conditions. Combining them requires the development of common inputs and outputs along with standard terminology, definitions, and other issues.

6. Conclusion

Limiting the impact of degradation on PV production is cost effective, as billions of dollars could be saved within the next decade when PV is expected to be a major energy contributor. The focus needs to be on the fundamental physical and chemical processes and not on specific technologies such that the understanding can be extrapolated to the newest technologies because of the pace of change in PV. New characterization tools may be required such that degradation mechanisms can be more directly observed. Modeling efforts need to complement and support the experimental work such that the models can be applied to different technologies. This will take time, tools, and commitment from a dedicated staff. Because of the complexity and possible interactions between fundamental processes, collaborative efforts between different organizations may be best suited, perhaps in a consortium type of effort. National laboratories could play a leading role in this transition, as they have some tools and modeling efforts available today. Failure and degradation data are commonly more easily shared with national laboratories because of their perceived market neutrality. All of this will require considerably more investments and the recognition of the importance that these mechanisms will play in commercial systems in the next 10 years. The time for these investments is today, such that in 10 years when PV is expected to be the major energy contributor worldwide, we may have answers and solutions to mitigate at least some degradation phenomena.

Appendix

If we could reduce annual system performance losses by any means from 0.75% year^{-1} to 0.5% year^{-1}, it would save the need to replace 0.25% of annual capacity. At approximately 1 TW, as in the example, that would amount to 2.5 GW that needed to be replaced annually. To estimate the cost, we use the median price of a 500 kW to 5 MW utility-scale photovoltaics (PV) system in the second half of 2022 from ref. [9] at US \$ 1.77/W_{DC}. Since this hypothetical example would be taking place in 2035, the dollar estimated amount needs to be converted to 2023 dollars by considering inflation that we estimate to be approximately 3%. Obviously, the last 2 years were an exception in terms of inflation but 2–3% annual inflation is closer to typical historical values. Using these cost assumptions, we arrive at a cost value of ≈\$ 3 billion to replace PV capacity lost because of degradation in 2035. Understandably, there are a lot of assumptions that could change the estimated replacement cost considerably; however, we hope to demonstrate that this is a substantial amount.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

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