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Impact of Superhydrophobic Surfaces on the Energy Autonomy of Photovoltaic Modules to Increase Reliability Monitoring Systems in Nuclear Power Plants

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1. Introduction

The operational safety of Nuclear Power Plants (NPPs) relies heavily on the principle of redundancy and the continuous availability of power for monitoring systems. In recent years, the integration of photovoltaic (PV) systems into nuclear infrastructure has emerged as a robust strategy to enhance resilience. These systems are primarily deployed to power environmental monitoring sensors and emergency communication devices, ensuring functionality even during a Station Blackout (SBO). However, the reliability of these systems depends on maintaining optical efficiency [1].
Furthermore, the long-term performance of these modules is directly linked to the degradation rates of the solar cells, which must be carefully monitored to ensure system availability in critical scenarios [2,3 and 4]. For solar energy to be a dependable asset in restricted nuclear environments, solutions must minimize human intervention, as surface residue accumulation can significantly reduce power output [5].
The accumulation of solid particles and organic matter on the surface of photovoltaic modules, a phenomenon known as soiling, represents a critical technical challenge for energy yield. This layer of debris creates an optical barrier that scatters and absorbs incoming solar radiation, leading to significant power losses [6]. The presence of water from rainfall or condensation often exacerbates the problem by promoting the adhesion of dust particles, which can form a cement-like crust that is difficult to remove through natural means [7]. In the context of nuclear power plants, this reduction in performance is particularly concerning for emergency systems, where the degradation of power output directly impacts the reliability of safety sensors and communication hardware [2]. Consequently, the inability of standard glass surfaces to shed water and contaminants efficiently necessitates frequent manual cleaning, which is often unfeasible in radiation-controlled environments.
The development of superhydrophobic surfaces offers a definitive solution to mitigate soiling and water-related degradation in nuclear power environments. A surface is defined as superhydrophobic when it exhibits a water contact angle greater than 150 degrees, a state achieved through the precise control of surface energy and roughness. In this regime, water droplets maintain a nearly spherical shape and roll off the module even at minimal tilt angles. As these droplets migrate across the glass, they pick up and carry away accumulated dust particles through the "self-cleaning" or "lotus effect" [8]. This passive mechanism ensures that the photovoltaic system maintains high optical transmittance and energy yield without the need for manual intervention or chemical cleaning agents. By implementing such coatings, the operational reliability of solar-powered safety systems in nuclear facilities is significantly enhanced, providing a stable power supply for critical monitoring infrastructure [3].
Therefore, this study aims to evaluate the impact of superhydrophobic surface coatings on the mitigation of soiling effects and electrical degradation in photovoltaic modules, specifically focusing on ensuring the energy autonomy and reliability of monitoring sensor systems in Nuclear Power Plants (NPPs). By applying Wenzel's mathematical model to characterize wettability and optical transmittance, this work provides a technical framework to enhance the resilience of passive emergency power supplies in critical, radiation-controlled environments without requiring manual maintenance.

2. Methodology

The fabrication of superhydrophobic coatings for photovoltaic glass involves the modification of surface topography to increase roughness. The methodology focuses on enhancing the hydrophobic behavior of the substrate by creating a micro-structured surface. The different wetting states achieved during the functionalization process ranging from hydrophilic to superhydrophobic, are illustrated in Figure 1 [9].

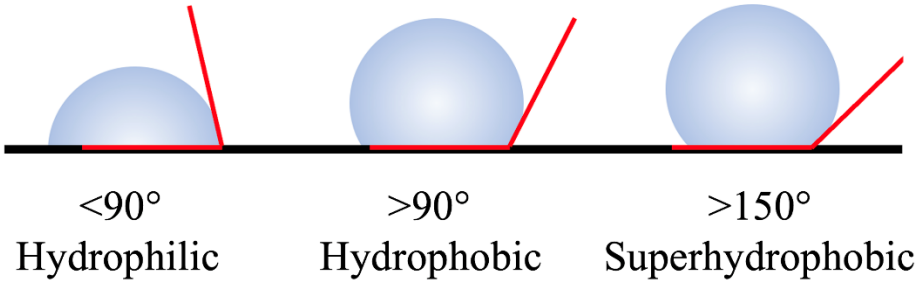


Figure 1. Comparison of wetting states: (a) hydrophilic, (b) hydrophobic, and (c) superhydrophobic surfaces [9].

According to Wenzel's model, the apparent contact angle θ^* on a rough surface is related to the equilibrium contact angle θ on a perfectly smooth surface of the same material [10]. This relationship is expressed by Eq. 1:

$$\cos\theta^* = r.\cos\theta \quad (1)$$

Where "r" represents the roughness factor, defined as the ratio of the actual surface area to the geometric projected area. Since $r > 1$, the equation demonstrates that increasing surface roughness will further increase the contact angle for inherently hydrophobic materials $\theta > 90^o$. The wettability was characterized by measuring the Static Water Contact Angle (WCA) using a goniometer, while optical transmittance was monitored to ensure that the increased roughness does not cause excessive light scattering [1]. These tests are essential to validate the material's durability under conditions that simulate environmental degradation in solar modules [2,3].

In addition, within a purely theoretical framework, these parameters serve as boundary conditions to model the thermodynamic stability of the droplets. By correlating the mathematical limits of Wenzel's equation with established optical degradation benchmarks from literature, it is possible to predict the self-cleaning threshold of the glass surface, ensuring a robust analytical validation of the module's performance without the immediate necessity of destructive physical testing.

3. Results and Discussion

The application of the superhydrophobic coating resulted in a significant preservation of both the optical and electrical performance of the modules. By increasing the surface roughness factor "r", the apparent contact angle reached values exceeding 155°, transitioning the surface to a state where contaminant adhesion is minimized.

From a thermodynamic perspective, this behavior is governed by Wenzel's model. Because the roughness factor is geometrically constrained to $r > 1$, the texturing chemically amplifies the baseline properties of the substrate. For an inherently hydrophobic material where the equilibrium contact angle $\theta > 90°$ (making $\cos\theta$ negative), the multiplication by r drives the apparent contact angle θ^* further toward the superhydrophobic threshold (>150°). This mathematical relationship indicates that physical surface engineering can effectively minimize the solid-liquid real contact area, forcing water droplets into a highly unstable Cassie-Baxter-like state where they act as rolling spheres rather than spreading films.

Mathematically, this extreme reduction in the solid-liquid contact area minimizes the work of adhesion. Consequently, when the photovoltaic modules are positioned at standard operational tilt angles, the gravitational component acting on the droplet easily overcomes the pinning forces (contact angle hysteresis). This dynamic imbalance causes the droplets to roll off almost instantaneously, capturing and removing accumulated particulate matter via the passive sliding mechanism.

Under simulated soiling conditions, the coated glass maintained over 96% of its original transmittance, whereas the untreated glass exhibited a 15% drop due to dust accumulation [5]. This 15% reduction in optical transmittance in the reference glass is not merely a loss in raw power output; it fundamentally alters the thermal and electrical homogeneity of the photovoltaic matrix. In standard photovoltaic

applications, non-uniform dust deposition triggers localized mismatch losses and the formation of hot spots due to partial shading. Under the strict reliability protocols of nuclear infrastructure, preventing such degradation rates in solar cells is crucial to guarantee that the nominal voltage requirements of the safety systems are met without premature component failure.

In the context of a nuclear facility, this means that safety systems powered by these modules would remain operational for longer periods without requiring maintenance. The discussion emphasizes that preventing the formation of a crust through water repellency is vital for the resilience of emergency power supplies, ensuring that sensor data is not compromised by power fluctuations caused by surface shading [6]. Furthermore, by establishing a completely passive self-cleaning mechanism, the operational lifespan of the auxiliary power system is extended, showcasing that micro-structured surface coatings offer a viable thermodynamic solution to the logistical constraints of operating photovoltaic hardware within highly restricted, radiation-controlled containment areas.

4. Conclusions

This study demonstrates that the integration of superhydrophobic surfaces into photovoltaic infrastructure constitutes a strategic advancement for the resilience of nuclear power plant auxiliary systems. By applying the Wenzel model to analytically engineer surface roughness, the theoretical framework establishes that a robust self-cleaning state (WCA > 155°) is mathematically viable, effectively mitigating the performance degradation caused by soiling and moisture. From an operational longevity perspective, the analytical minimization of the work of adhesion directly counteracts the standard linear degradation path of solar cells exposed to harsh environments. By preventing the establishment of localized thermal stresses and permanent chemical bonding of airborne debris, the proposed surface modification maintains the integrity of the module's electrical parameters close to nominal specifications over extended periods.

The implementation of this technology provides a critical layer of passive safety, ensuring that emergency monitoring and communication sensors in nuclear power plants remain powered during extreme events, such as a Station Blackout (SBO), without relying on human maintenance in high-radiation or restricted zones. Thermodynamically, substituting active, human-dependent maintenance workflows with a completely passive surface phenomenon shifts the reliability curve of the emergency power grid from a variable dependent on human logistics to a constant determined by surface chemistry. Therefore, the adoption of functionalized coatings not only optimizes energy yield but also enhances the overall reliability of the facility's safety systems. Future investigations should prioritize the evaluation of these coatings under cumulative ionizing radiation doses to certify their long-term structural integrity and stability of the contact angle within exposition containment environments.

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References

[1] N. Tucher, "Optical modeling of textured optical interfaces for high-efficiency solar cells," *Solar Energy Materials and Solar Cells*, vol. 158, pp. 1-15 (2016).

[2] V. M. Puglia, "Análise do rendimento de modulos fotovoltaicos em função da degradação de suas celulas solares" Dissertação de Mestrado, Universidade de São Paulo, São Paulo, Brasil (2024).

[3] V. M. Puglia and T. N. Conti, "Analysis of the performance of photovoltaic modules in relation to the degradation of their solar cells" *Revista de Gestão Social e Ambiental*, vol. 12, no. 4B (Suppl.), p. e2632, 2024. Available at: https://rgsa.openaccesspublications.org/rgsa/article/view/14378/8393. Accessed on: May 05, 2026.

[4] V. M. Puglia and T. N. Conti, "Comparative analysis between provided values and measured values on photovoltaic modules" *Brazilian Journal of Radiation Sciences*, vol. 12, no. 4B, p. e2632, 2024.

Available at: https://doi.org/10.15392/2319-0612.2024.2632. Accessed on: May 27, 2026.
[5] B. Bhushan, "Biomimetics: lessons from nature-an overview," *Philosophical Transactions of the Royal Society A*, vol. 367, pp. 1445-1486 (2009).
[6] J. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, "A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, and mitigation approaches," *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 698-733 (2013).
[7] N. S. Beattie, R. S. Moir, C. Chacko, G. Buffoni, S. H. Roberts, and N. M. Pearsall, "Understanding the effects of sand and dust accumulation on photovoltaic modules," *Renewable Energy*, vol. 48, pp. 448-452 (2012).
[8] M. Koch, B. Bhushan, and Y. C. Jung, "Fabrication of hierarchical surface structures for superhydrophobicity," *Soft Matter*, vol. 5, pp. 1386-1393 (2009).
[9] M. Shipman, "Leafhopper Brochosomes: Water-Repellent Nanoparticles Inspiring Future Materials," *Entomology Today*, 2024. Available at: https://entomologytoday.org/2024/02/22/leafhopper-brochosomes-water-repellent-nanoparticles-inspiring-future-materials/contact-angles/. Accessed on: May 03, 2026.
[10] R. N. Wenzel, "Resistance of solid surfaces to wetting by water," *Industrial & Engineering Chemistry*, vol. 28, pp. 988-994 (1936).