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Quantifying The Albedo Effect For PV Modules:

Methods, Measurements, And Practical Impact

Thor Brubakken

Eng. Arezoo Safaei Naraghi

R&D Department

Bridgehill• 2026

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1. Introduction

Photovoltaic modules are commonly classified as monofacial or bifacial depending on whether they convert solar radiation from one or both sides of the module. Monofacial modules generate electricity only from the front surface, while the rear side is optically inactive; therefore, ground- or roof-reflected irradiance does not contribute to their energy production.

Bifacial modules, in contrast, are optically active on both sides and can convert not only direct and diffuse irradiance on the front side but also reflected irradiance incident on the rear side. As a result, the energy yield of bifacial systems depends strongly on the reflectivity of surrounding surfaces, making surface *albedo* a key design parameter.

Albedo describes the fraction of incoming solar radiation that is reflected by a surface, expressed on a scale from 0 to 1. The relevance of albedo is particularly pronounced in regions with low solar elevation, high diffuse irradiance, and seasonal snow cover, where reflected light can contribute a substantial share of the total irradiance reaching the rear side of bifacial modules. At the same time, rear-side irradiance is non-uniform and varies with system geometry, surface type, and weather conditions, making the albedo effect both an opportunity and a design challenge.

Unlike many performance enhancements, albedo optimization is achieved through surface selection and system design, making it a cost-effective lever for improving both technical performance and project economics. This article summarizes how the albedo effect can be measured, modeled, and validated for real PV systems, and what this means for production, economics, and system design.

2. Literature review

2.1. Albedo Effect in Monofacial versus Bifacial PV Systems

The relevance of albedo differs fundamentally between monofacial and bifacial photovoltaic technologies. Monofacial modules convert solar radiation only on the front surface, and reflected irradiance from the ground or roof does not contribute to energy production. Consequently, changes in surface albedo have a negligible effect on annual energy yield. Vasilakopoulou et al. (2023) report that monofacial systems gain only about 0.7% in annual energy yield per 0.1 increase in albedo, primarily due to indirect thermal or diffuse-light effects.

Bifacial modules, in contrast, are optically active on both sides and can convert reflected irradiance incidents on the rear surface. As a result, their energy yield is strongly dependent on surface reflectivity. According to Vasilakopoulou et al. (2023), bifacial systems gain approximately 4.5% per 0.1 increase in albedo, leading to typical annual energy gains of 10–20% compared to monofacial systems. Under highly reflective conditions, reported gains can reach 20–30%, particularly in environments with high diffuse irradiance or snow cover.

2.2. Effect of Underlayment Albedo in Bifacial PV Systems

While bifacial modules benefit from albedo in general, the magnitude of this benefit depends on the reflectivity of the surface beneath the modules. Studies focusing exclusively on bifacial systems show that low-albedo surfaces, such as dark roofs or soil, provide limited rear-side irradiance, whereas high-albedo surfaces significantly enhance energy production.

Pirouz et al. (2025) demonstrate that increasing surface albedo from 20% to 80% leads to an 8–15% increase in bifacial energy yield, based on simulations using long-term meteorological data. These results highlight that engineered reflective surfaces can systematically improve rear-side irradiance beyond what is achievable on conventional dark underlayments. In snow-dominated climates, Kahl et al. (2019) further show that natural high-albedo conditions can increase annual energy yield by approximately 10–12%, with even higher gains during winter months.

This separation clarifies that the first comparison addresses technology type (monofacial vs bifacial), while the second isolates the optical optimization of bifacial systems through underlayment albedo.

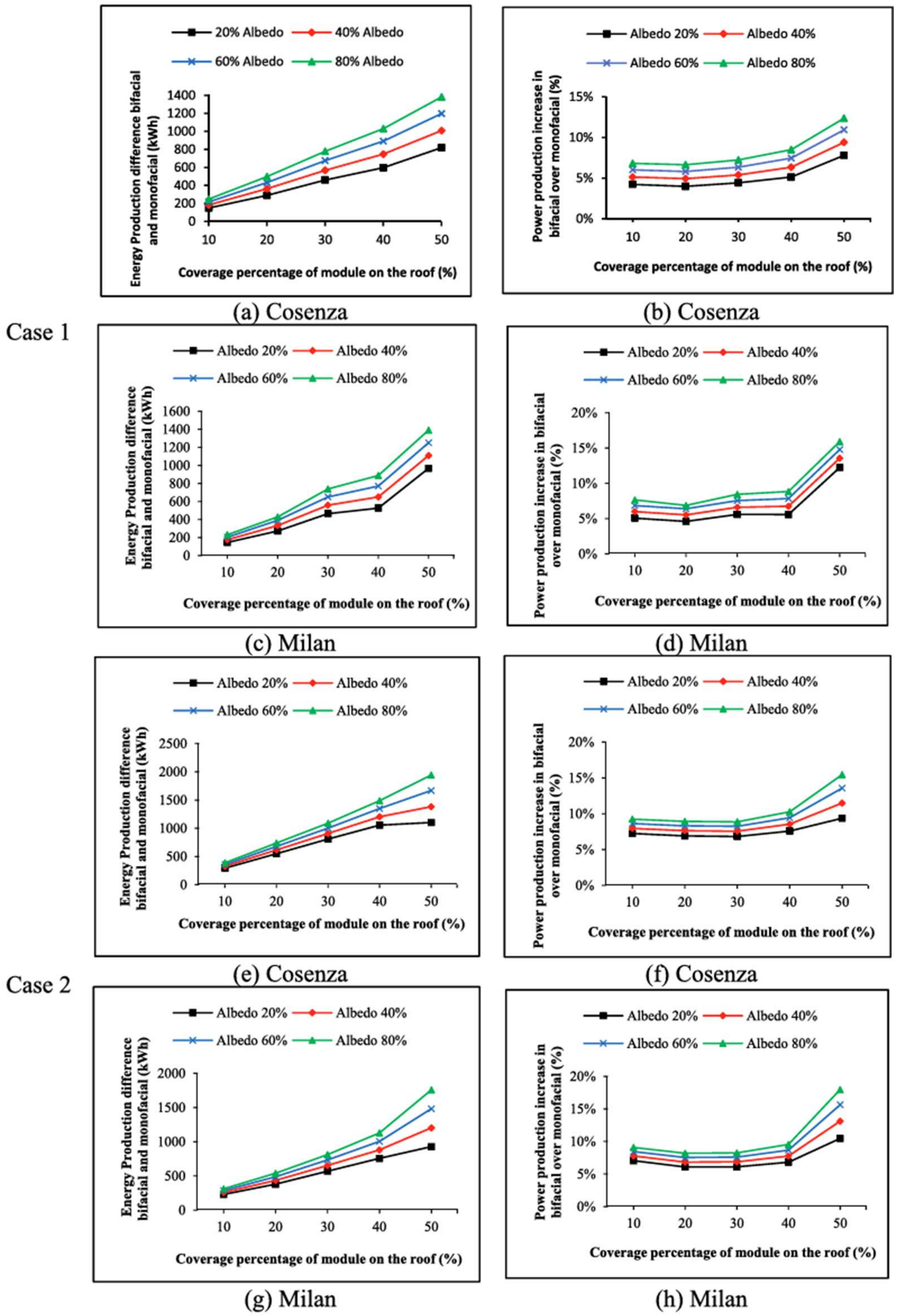

Figure No.1: Panels (a), (c), (e), (g): Energy production difference (kWh), Panels (b), (d), (f), (h): same information but expressed as percentage. Higher albedo = higher bifacial advantage.

2.3. Industry Case Study: Effect of Underlayment Albedo (Black vs. White)

In addition to academic literature, recent internal field measurements conducted by Bridgehill Engineering Lab provide practical confirmation of albedo-driven gains under real rooftop conditions. The study compared identical bifacial PV strings installed above a low-albedo black surface and a high-albedo white polymer surface on a commercial flat roof in Southern Norway. Over a full measurement period, the reflective surface delivered an average 6.1% increase in annual energy yield, corresponding to 11.4 kWh/m² per year, with peak rear-side contributions reaching up to 11% of front-side irradiance during summer months.

These results demonstrate that albedo optimization can deliver measurable, bankable energy gains in high-latitude climates without changes to modules or electrical design, reinforcing the relevance of albedo as a practical design parameter for commercial rooftop PV systems. Full results are documented in a separate Bridgehill Engineering Lab publication (Brubakken, 2025).

Figure No.2 illustrates the monthly energy production measured in Bridgehill's field study, comparing bifacial PV modules installed over a white reflective surface and a black low-albedo surface. The graph shows that the white surface consistently delivers higher production throughout most of the year, with the largest gains occurring from spring to late summer.

During winter months, the difference is smaller due to low solar elevation and limited reflected irradiance. This seasonal pattern confirms that albedo-driven gains are strongest when solar angles and diffuse radiation conditions allow more reflected light to reach the rear side of the modules, supporting the quantitative results reported in the Bridgehill case study.

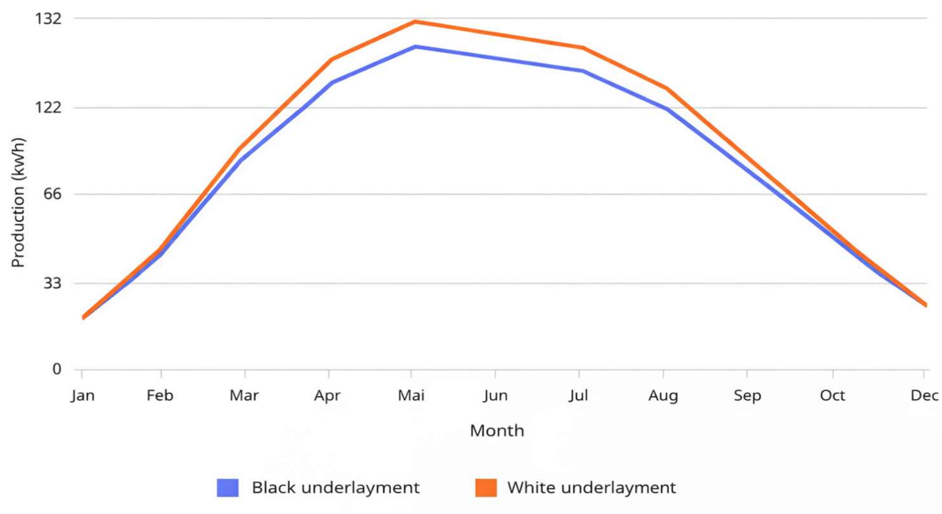

Figure No.2: Monthly energy production with seasonal pattern

Based on research conducted at the Bridgehill Engineering Lab, controlled testing of bifacial photovoltaic modules installed over a white membrane shows an annual energy yield increase of approximately 7.6% compared to monofacial modules. In addition, field measurements of bifacial photovoltaic modules installed over the same white membrane show an average annual energy yield increase of approximately 6.1% compared to monofacial modules.

Figure No.3 demonstrates the monthly energy production based on Bridgehill Engineering Lab measurements, comparing monofacial PV modules with bifacial PV modules installed over black and white underlayments. The results show consistently higher production for the bifacial system with a white underlayment, particularly during spring and summer months.

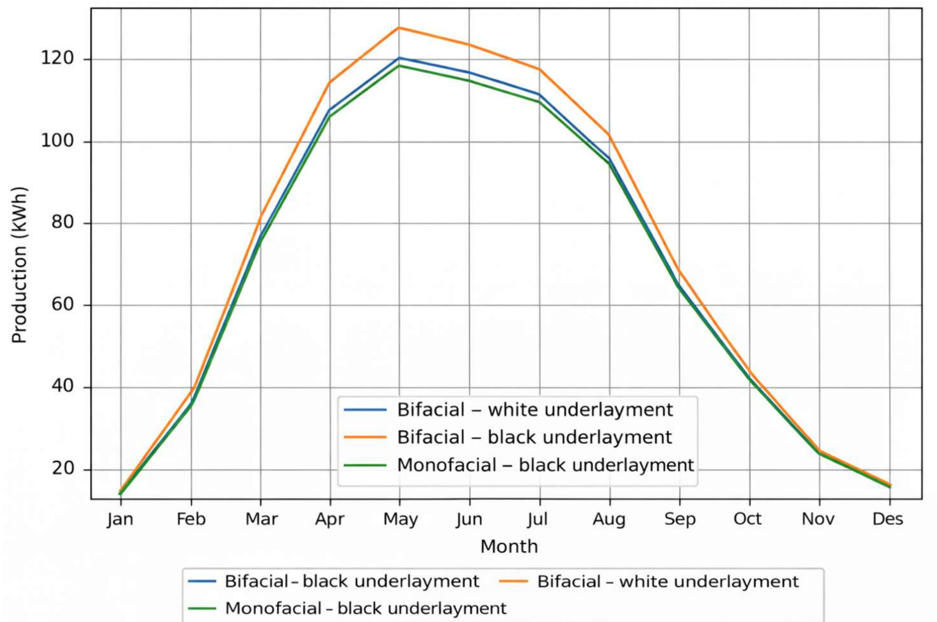

Figure No.3: Monthly energy production for monofacial, bifacial with black underlayment and bifacial with white underlayment.

2.4. Core Key Takeaways

Monofacial PV systems show negligible albedo-related energy gain (≈ 0%), as reflected irradiance does not contribute to power production.

Bifacial PV systems installed over low-albedo (black) surfaces achieve modest annual energy gains of approximately 2–6%, primarily from diffuse and indirect irradiance.

Bifacial PV systems combined with high-albedo (white) surfaces deliver substantial energy gains of 10–20%, with peak gains up to 30% under optimal or snow-covered conditions.

3. Methodology for Measuring and Modeling Albedo Effects

A clear methodology is essential when measuring albedo effects, as albedo varies with surface type, weather, and season, and these changes strongly influence rear-side irradiance.

Norwegian University of Science and Technology (NTNU) used a structured, real-world testing approach to study the albedo effect. Their experiments were carried out on outdoor PV test fields using natural ground surfaces such as soil, grass, concrete and snow, each with different albedo values measured directly in the field (Martinsen, 2022).

The work was performed under actual Norwegian winter and spring conditions, including clear sky, partly cloudy and overcast days, with temperatures as low as –12°C, allowing them to capture how changing sky conditions affect reflected light. They supplemented these field measurements with controlled laboratory reflectance tests on white and black tarps to isolate how different surface brightness levels influence the rear-side irradiance of bifacial panels.

3.1. NTNU's Approach to Measuring and Modeling Albedo Effects

- **Irradiance Measurements**

Measuring front and rear irradiance with calibrated sensors and filters the data to remove errors. This ensures the irradiance used in the analysis reflects real, accurate conditions.

- **Ground Surface Characterization**

Measuring how different surfaces (soil, grass, snow, concrete, tarps) reflect light, both in the field and in the lab. This provides reliable albedo values instead of relying on assumptions.

- **3D Modeling and Ray-Tracing**

NTNU builds a detailed 3D model of PV installation and uses ray-tracing to see how light reaches the rear of the modules. This captures shading, geometry, and uneven rear illumination.

- **Electrical Performance Modeling**

The irradiance patterns from the 3D model are fed into an electrical model to estimate bifacial gain, mismatch losses, and overall energy output. This shows how albedo affects real power production.

4. Results From Controlled Albedo Experiments

4.1. Key Findings

The tests showed a clear difference between bright and dark surfaces. The white, highly reflective surface increased the light reaching the back of the bifacial panels by 5–11%, while the black surface contributed almost nothing. This confirmed that brighter ground surfaces directly boost rear-side irradiance and therefore potential energy gain. The measurements also matched well with the modeled results, showing that accurate albedo data is important for reliable performance predictions.

Connecting academic research to industry and real-world practice is essential for creating value in solar installations. The experiments also showed that even with good albedo, the rear side of a panel does not receive light evenly. Parts of the panel are shaded by the mounting structure, wiring, or other panels, causing some cells to get less light than others.

This uneven illumination can lead to 1–3% annual energy loss, and short-term losses can be higher when the sun is low. NTNU observed the same effect in their field studies, highlighting that both albedo and uniformity are important for maximizing bifacial performance. This raises important considerations for roof designers and solar installers, such as roof angles, mounting layout, and the surface material beneath the panels all play a significant role in how usable reflected light reaches the rear side.

5. What Does Albedo Mean for Consumers and Investors?

Research shows that brighter, more reflective surfaces can meaningfully increase the energy production of solar panels, especially bifacial systems. When albedo rises from low levels (around 20%) to highly reflective surfaces (around 80%), bifacial output increases by roughly a factor of 1.1 to 1.3 compared to darker surfaces.

According to the studies referenced in this paper, this improvement consistently appears as a substantial gain, equivalent to producing several months' worth of extra energy over the lifetime of a system. For investors, this means higher production from the same installation and a stronger overall return.

In simple terms:

Higher albedo means higher energy yield, better system performance, and a more profitable solar installation.

6. Practical Recommendations

6.1. For system owners

- Maintain clean, bright ground surfaces where possible.
- Avoid dark stones, asphalt, or absorbing membranes directly under arrays.
- Use reflective membranes for flat roofs.

6.2. For designers & engineers

- Model albedo dynamically (monthly or event-driven).

- Measure local reflectance where feasible.
- Include 3D structural shading in all bifacial simulations.
- Use calibrated rear-side sensors for validation.

6.3. For investors

- Expect 5–12% bifacial gain depending on geometry and ground cover.
- Confirm that the design includes rear mismatch modeling, not just front-side yield projections.

7. Limitation of the study

This study synthesizes findings from research that examined specific PV technologies, roof configurations, and installation geometries. The underlying evidence base is therefore limited in the following ways:

7.1. Limited Range of PV Technologies

The referenced studies focus primarily on crystalline silicon monofacial and bifacial modules, tested under controlled tilt and height conditions. Other PV technologies such as thin-film, HJT, TOPCon, Perovskite tandem modules, and façade-integrated PV, were not included, restricting the applicability of the results to a narrow class of PV systems.

7.2. Restricted Roof Types and Surface Conditions

The analyses rely mostly on flat commercial roofs, cool roof membranes with increased albedo, and in the case of snow-focused studies, snow-covered ground treated as the reflective surface. Real-world roof variability (pitched roofs, aged or weathered coatings, gravel roofs, green roofs, metal roofs, and mixed-surface buildings) was not represented, even though such conditions significantly influence effective albedo and PV performance.

7.3. Simplified Installation Geometries

Investigations examined PV arrays as single, isolated systems with uniform tilt angles, typically 13°–40° in urban cool-roof studies and 65°–90° in mountain/snow studies. Bifacial systems were tested at heights between 0–2 m. Complex installation realities such as irregular layouts, varying row heights, or PV density effects were outside the scope of existing studies.

7.4. No Multi-Array or Urban Interaction Effects

Existing work does not address how multiple rooftop PV installations interact by altering local albedo, mutual shading, view factors, or rear-side irradiance. Likewise, urban canyon effects, reflections from adjacent façades, and district-level heat flows were not modeled. These interactions can substantially modify albedo-driven gains and therefore represent a major research gap.

7.5. Climate and Seasonal Assumptions

The studies rely on specific climatic datasets (e.g., Zurich, Oslo, Cairo, Shanghai) and assume stable reflective conditions, either persistent snow cover or clean high-albedo roof coatings. In practice, snow reflectance varies with melting and contamination, while cool roofs degrade quickly. This limits the transferability of results across climates and seasons.

7.6. Simplified Energy and Albedo Modeling

Several studies use steady-state or constant albedo values, simplified irradiance assumptions, or PV models that do not simulate full electrical behavior. Time-varying spectral albedo, soiling, thermal cycling, and electrical mismatch losses were largely excluded. As a result, findings provide relative performance trends rather than exact predictions for real installations.

8. Future contributions

Future work should broaden the PV technologies studied, include more realistic roof types and aging conditions, and model how multiple PV arrays and buildings interact through shading and reflections.

More accurate results will require dynamic albedo data and long-term field measurements across seasons and roof surfaces. Urban-scale simulations are also needed to understand PV-albedo effects on cooling demand, heat islands, and total energy yield. To turn this research into practical value for industry and end users, future studies must translate these insights into design guidelines, installation standards, and decision-support tools that reflect real-world conditions.

9. Conclusion

This study demonstrates that the albedo effect is a measurable, controllable, and economically relevant driver of energy yield in bifacial photovoltaic systems. Through a combination of literature review, controlled experiments, and industry-scale field measurements, the work shows that surface reflectivity directly governs rear-side irradiance and therefore bifacial gain.

The results confirm three distinct performance scenarios: monofacial systems show negligible sensitivity to albedo, bifacial systems over low-albedo surfaces achieve only modest gains, and bifacial systems combined with high-albedo underlayments deliver substantial and repeatable increases in annual energy production. Measurements from Bridgehill Engineering Lab verify that reflective roof membranes can increase annual yield by approximately 6–8% under real Nordic rooftop conditions, with rear-side contributions reaching up to 11% during favorable periods.

Overall, this work demonstrates that albedo optimization is a practical and low-cost pathway to improving return on investment in bifacial PV systems. By combining validated field measurements with established research, the study provides clear evidence that thoughtful surface selection and albedo-aware design can unlock measurable, bankable value, turning bifacial PV from a theoretical advantage into a predictable financial benefit.

By sharing validated data and practical insights, the Bridgehill R&D department aims to support better-informed decisions across the solar industry and contribute to the broader societal transition toward more efficient and reliable renewable energy systems.

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