Performance and aesthetic evaluation of building-integrated photovoltaics with MorphoColor® and antisoiling coatings in a living lab environment

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***Abstract*—This study evaluates the performance and subjective perception of photovoltaic (PV) panels featuring MorphoColor® and antisoiling coatings installed in the ZEB Living Lab at Gløshaugen campus (Norwegian University of Science and Technology). The objective analysis tracked energy production, efficiency, and environmental conditions over nearly a year, revealing that panels with antisoiling coatings performed slightly worse than those without when subjected to similar solar irradiance levels. A similar conclusion applies to the color effect of the MorphoColor® coating, which lowers the annual energy yield of the PV module by approximately 6% compared to the black reference. This reduction aligns with the efficiency losses previously reported for MorphoColor® technology. Subjective assessments gathered through more than 80 standardized interviews highlighted a preference for black solar panels that "blend in" with the aesthetics of the ZEB living lab. However, these preferences reflect the specific architectural context and limited color options (black and blue) that the survey offers. Preferences may differ in different settings, with a broader range of PV colors or other building types. Some respondents also suggested that colored panels could be integrated creatively and visibly, especially if better aligned with surrounding architectural features. The results underscore the importance of balancing technical performance with public aesthetic preferences to enhance solar technology adoption - an objective that can potentially be better achieved through engagement with potential building users prior to the introduction of MorphoColor® technology. Key findings include seasonal performance trends, the impact of shading, and divergent public opinions on solar panel visibility. This work contributes to the discourse on sustainable building design by addressing both functional and perceptual aspects of PV installations.**

Keywords*—photovoltaic panels; anti-soiling; MorphoColor®; building-integrated PV; aesthetic perception; living lab;

I. Introduction

Integrating photovoltaic (PV) panels into buildings is critical for advancing sustainable energy solutions, yet their adoption hinges on both technical performance and public acceptance. While efficiency and durability are well-studied, the aesthetic impact of PV panels remains a significant barrier. This study addresses this gap by examining PV panels with MorphoColor® and antisoiling coatings in the ZEB Living Lab, combining objective performance metrics with subjective user evaluations. The research aims to (1) quantify the energy output and efficiency of coated panels under real-world conditions, (2) assess the influence of environmental factors like shading and seasonal variations, and (3) evaluate public perceptions of PV aesthetics. Our contributions include empirical data on panels' efficiency with two types of coatings, insights into design preferences, and recommendations for balancing functionality with visual appeal in urban solar deployments.

Prior research has demonstrated the benefits of antisoiling coatings in reducing dust-related efficiency losses, particularly in arid regions [1]. MorphoColor® coatings [2], inspired by structural coloration, have been explored for their potential to enhance visual appeal without significant efficiency trade-offs [3]. Studies on public perception highlight a preference for minimally visible PV installations, though cultural and contextual differences exist [4]. This study builds on these foundations by testing coatings in a Nordic climate and incorporating qualitative feedback from diverse stakeholders.

II. Methodology

A. Objective characterization

Four types of PV modules were mounted on the façade of the ZEB Living Lab: standard black panels, black panels with an antisoiling coating, panels with a MorphoColor® coating, and panels featuring both morpho and antisoiling coatings. **Error! Reference source not found.** shows the architecture of a system for monitoring PV performance. The DAQ system, built around a Raspberry Pi [4], monitored surface temperatures using two MCP9808 sensors (±0.25 °C accuracy) on the reference black and MorphoColor® panel [5]. The information on the outdoor temperature and solar irradiance on the façade was collected using the living lab monitoring system and measured by a Second Class pyranometer and a Class B Pt100 resistance temperature detector (RTD). The pyranometer was located on the same wall with the same orientation as the panels, with a distance of around four meters between them. Outdoor temperature was monitored with a weather station located on the living lab roof. Real-time tracking of PV energy generation by measuring power and voltage output and generated current was done through PV inverters and a separate monitoring solution, the Tigo Energy System.

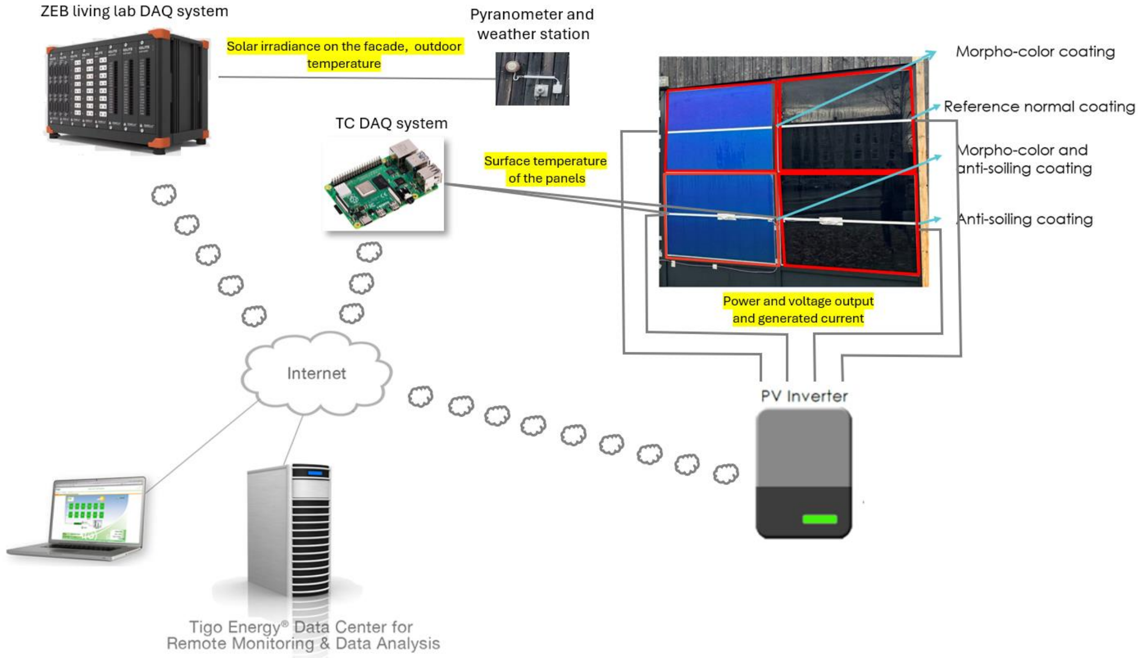

Fig. 1. Architecture of the system for monitoring PV performance in the ZEB living lab

The PV panels' performance and the surrounding environment were monitored for nearly a year. However, due to unforeseen circumstances, the living laboratory was out of operation from the beginning of September 2024, resulting in missing data from September 9 to October 17 to complete year-round measurements. PV energy production was recorded every minute, but the analysis focused on hourly, daily, and monthly outputs. Ambient temperature, incident solar radiation on the façade, and surface temperatures of the PV panels were measured at sub-minute intervals, with the analysis based on hourly, daily, or monthly averages or cumulative values.

B. *Subjective characterization*

The qualitative evaluation of building-integrated PVs was done in the fall of 2023 with the help of student assistants. More than 80 standardized interviews were conducted with users of the Gløshaugen campus, where building-integrated PVs are located. The questionnaire, which consisted of 17 questions, explored the informants' subjective aesthetic evaluations of the test case and PV on buildings in general. As expected for campus use, students were overrepresented in the sample (more than 70%), where more than 90 % of the respondents were aged between 20 and 30 years

III. RESULTS

A. *Objective characterization*

The average daily photovoltaic energy by month, produced by four types of panels, along with the standard deviation of daily photovoltaic production, is shown in **Error! Reference source not found.**. The highest PV production occurs in March and April, mainly due to the panels' vertical south-facing orientation, the solar path, and reduced cloud cover. PV production in September and October may be comparable to that in March and April. However, since data from September 9 to October 17, 2024, is missing, a definitive conclusion cannot be drawn, and the gap needs to be supplemented to complete the full-year measurements. From late April through May, June, July, and early August, the lower PV modules (those with an antisoiling coating) begin to outperform the upper modules (reference and MorphoColor®).

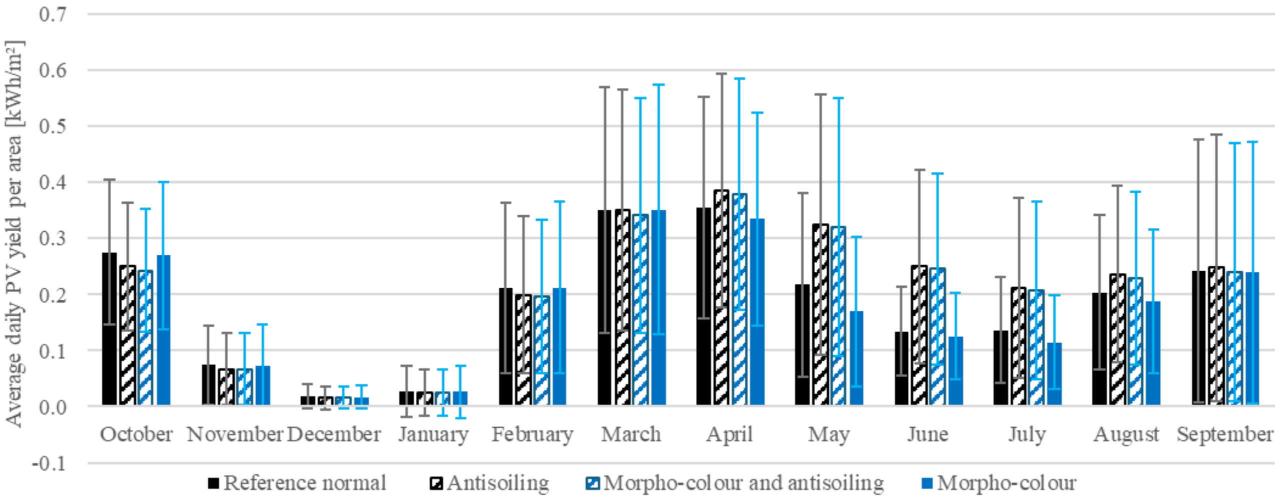

Fig. 2. Average daily photovoltaic energy by month

The effect becomes evident due to the sun's position and a slightly protruding façade element that creates a shadow that partially covers the upper panels, see **Error! Reference source not found.**.

Fig. 3. A shadow formed by the building design at the top panels, noticeable in the warmer part of the year

The average monthly efficiency of the four types of PV panels is shown in Figure 5. The efficiency of the PV panels was not available for all days in the months since the data on solar irradiance measured on the façade was not available continuously due to the LL DAQ system not operating continuously. Higher efficiency is observed for all types of panels during the transitional months (October to November and February to April) compared to the winter and summer months. Lower efficiency in December and January might be due to the frost formation (evident in Figure 6), while in summer, the reason most likely lies in the shading effect and the higher panels' temeprature. For example, in the three-week sequence from summer 2024 (03 June - 23 June, Figure 4), panel temperatures exceeded 50 °C on eight separate days, even if the ambient air temperatures were mild and did not exceed 25 °C during peak time. Solar irradiance on days with high panel temeprature exceeded 600 W/m^2.

Due to the shading effect of the facade, the efficiency of panels without antisoiling coating (top panels) significantly decreases during warmer months. However, when the panels are exposed to a similar amount of solar irradiance, the panels without the antisoiling coating slightly outperform those with the coating, as seen in the colder part of the year. Furthermore, it can be concluded that the MorphoColor® coating slightly reduces the panels' efficiency, as seen from the year-round comparison of monthly power output and efficiency between black panels and those with MorphoColor®. The annual energy yield of the MorphoColor® module is approximately 6% lower than the black reference.

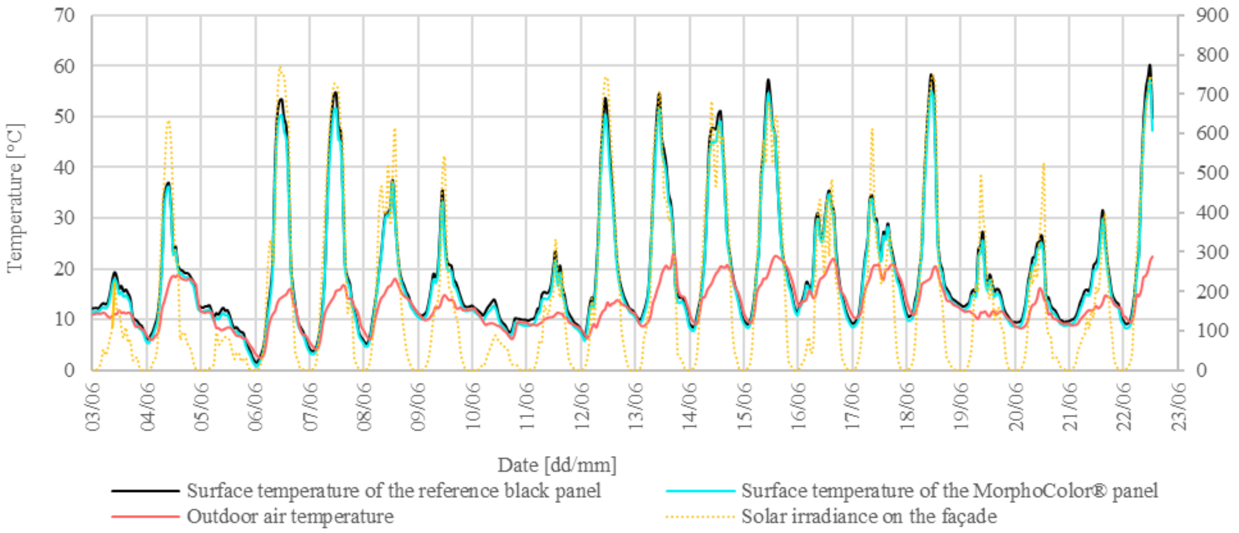

Fig. 4. Surface temperature of the reference black (blue) and MorphoColor® (orange)

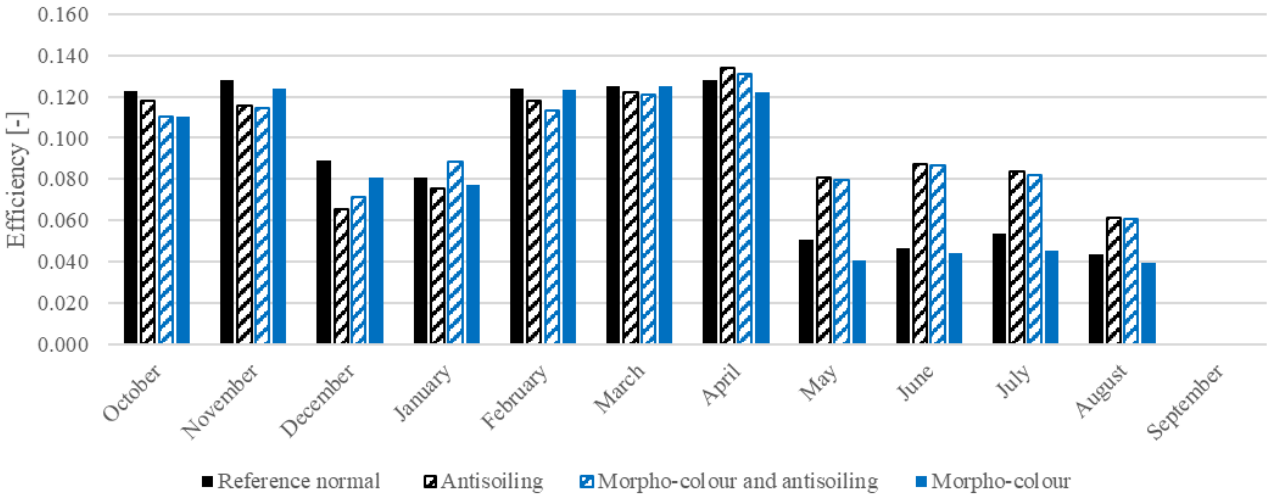

Fig. 5. Average efficiency by months

An analysis of the average daily PV production over the entire monitoring period (**Error! Reference source not found.**) reveals the following performance ranking, from highest to lowest: black panels with antisoiling coating, MorphoColor® panels with antisoiling coating, standard black panels, and MorphoColor® panels without antisoiling treatment.

TABLE I. AVERAGE PHOTOVOLTAIC ENERGY PER DAY FOR THE ENTIRE MONITORING PERIOD (OCTOBER 18, 2023 – SEPTEMBER 8, 2024).

Type	**Average photovoltaic energy per day normalized per panel area [kWh/m^2]**
Reference normal	0.179
Antisoiling	0.210
MorphoColor® and antisoiling	0.206
MorphoColor®	0.168
Note: the worse performance of samples without antisoiling coatings is influenced by their placement in the top row, which was in the warmer part of the year, shaded by the slightly protruding façade element	

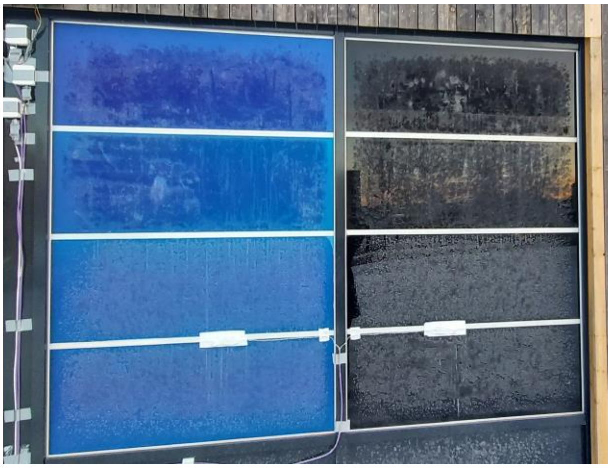

Fig. 6. Frost patterns on the PV panels

Panels without antisoiling coating tend to accumulate more dust. However, this difference is only noticeable when one is in close proximity to the panels. Furthermore, frost forms differently on panels with and without antisoiling coatings (Figure 6). The lower panels (with antisoiling) accumulate more frost. However, this was an unexpected outcome due to their increased hydrophobicity. A temperature inversion on clear, cold winter days and stronger radiative cooling near the ground may cause this phenomenon.

B. Subjective characterization

The majority of participants are young, primarily students studying at the Gløshaugen campus. About half of the respondents knew where the ZEB living laboratory was located, and slightly less than a quarter knew what the function of this facility was. Over half of the respondents were unaware of the building's solar panels. Additionally, approximately two-thirds of the respondents were completely unaware of any other solar technologies on or around the campus. This low level of awareness might not mean that students weren't paying attention, but rather that they didn't expect to see solar panels. Solar panels are still not very common on buildings in Norway, especially in cities. Because of this, people might be more used to simple building designs, and might see solar panels as something that doesn't fit in.

The survey results in Figure 8 display respondents' preferences regarding the appearance of solar technology facing the road, preferred colors, perceptions of the ZEB LL façade's complexity, and interest or experience with solar technology, with answers given on a 1 to 6 scale. The general impression is that respondents in this particular context tend to prefer black solar panels. However, for all people, it does not seem like color is the main issue when we discuss solar panels and the aesthetic of the building. Many wrote that the solar panels had to "blend in"; this may be the keyword. On whether there should be more buildings on Gløshaugen campus with more solar panels, almost everyone wrote "YES" because it was green, future-thinking, climate-friendly, renewable, or cool. Most people seemed positive about solar technology, and some also thought that NTNU "should lead by example." However, some people were more hesitant and questioned the cost and degree of climate friendliness.

Many more people wanted the solar panels to be black, whereas 46 people wished them to be black. Eight people wanted them to be blue, whereas someone wrote, "Blue = ugly, Black = nice. The people who wanted the solar panels to be black also wanted them hidden, preferably on the roof. For example, someone wrote, "Black with minimalistic appearance and design." It seems like there is an interpretation that black is the color that will be the least visible, so it does not affect the building's appearance.

Some of the informants also expressed concern for historic and older buildings. Often, they wrote that the solar panels had to be hidden, but do they? Many older buildings do not have black roofs, and one wrote, "Terracotta colors that resemble the color of a roof." Everyone seems to agree that the building's appearance is essential, and, therefore, the solar panels must blend in, but they have different ideas on how to blend in.

It should be emphasized that these preferences reflect the specific options (black and blue) and the particular architectural context of the ZEB Living Lab at the NTNU campus. In other settings, with a broader range of color options or different building types, preferences may vary significantly. Therefore, conclusions about preferred solar panel color should be interpreted in light of this specific survey context. Moreover, while the specific MorphoColor® sample used in the ZEB Living Lab had a strong, vivid color that may have stood out more than blended in, colored PV panels in general have the potential to harmonize with a building's façade and materials, especially when thoughtfully selected to match architectural features. This could lead to them being perceived less as PV elements and more as an integrated part of the building's design.

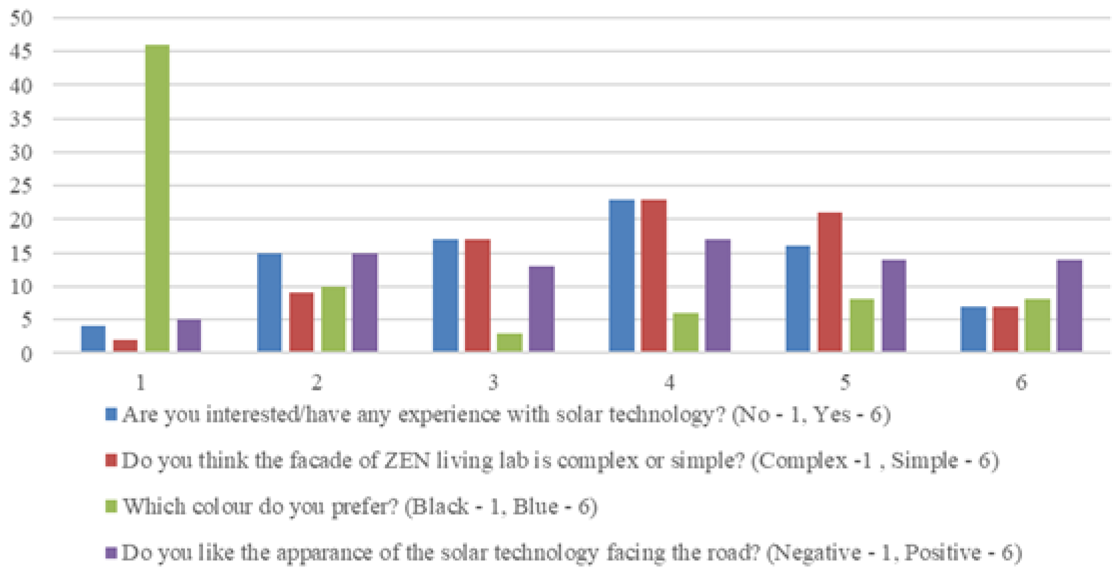

Fig. 7. The survey results on aesthetic preferences and perceptions of solar technology

IV. CONCLUSIONS

The analysis of the key performance indicators shows that PV panels with antisoiling coatings deliver the highest average daily energy production throughout the monitoring period. The antisoiling-only panel slightly outperformed the one with both MorphoColor® and antisoiling coatings, whereas overall, it outperformed 15 to 20% of panels without antisoiling coating. Seasonal trends revealed that the observed difference in efficiency during the warmer months (April–September) was due to shading caused by façade elements, which significantly reduced the performance of the upper panels (those without antisoiling coating). However, if exposed to similar incident solar radiation, panels without an antisoiling coating show slightly better performance, as evident in colder months (October–March). Also, MorphoColor® panels show slightly worse performance than black panels. Both outcomes are something to be expected, given that the output power of panels without coatings tested in the lab is marginally higher.

Furthermore, Trondheim is not considered an area with elevated particulate matter, so the accumulation of dust and particles on the surface was not large enough to significantly affect the panels' performance without an antisoiling coating. This is confirmed by the fact that the difference in dust accumulation on the panels was barely noticeable through visual inspection and only apparent upon close examination. Frost forms differently on panels with and without antisoiling coatings, with the lower coated panels accumulating more frost, an unexpected result due to their increased hydrophobicity, likely influenced by temperature inversion and stronger radiative cooling on clear, cold winter days. Although data gaps from September and October limit the full-year assessment, observed trends suggest similar behavior of panels as in March and April, respectively.

The subjective evaluation of the TC2 system and the ZEB Living Lab reveals a generally positive, yet nuanced, perception among respondents, most of whom were young students affiliated with the Gløshaugen campus. While roughly half of the participants knew the ZEB Living Lab's location, fewer knew its actual function, suggesting a communication gap about the lab's purpose. Interest in solar technology varied, with many expressing personal or work-related motivations, though their written responses often lacked elaboration. Most participants supported the broader use of solar panels at Gløshaugen (NTNU campus in Trondheim), associating them with climate-friendliness and NTNU's leadership in sustainability. However, some raised critical points about production-related emissions and Norway's low solar yield, reflecting a need for a greater public understanding of renewable energy trade-offs.

Aesthetic perceptions also played a key role. Most respondents preferred black solar panels, viewing them as less visually intrusive and more compatible with traditional architecture. Many expressed a desire for panels to "blend in," favoring minimalist or hidden installations, especially on rooftops. At the same time, there were varied interpretations of what it means to "blend in," especially when considering different building types or historical architecture. Some informants, for instance, noted that black may not suit red-tile roofs and suggested alternative tones.

It is important to note that these preferences emerged within a specific context, limited to black and blue panel options and the architectural setting of the ZEB Living Lab. In other settings, aesthetic preferences might differ significantly where a broader spectrum of colors or different design constraints apply. While the MorphoColor® panels tested had a vivid tone that may not have blended in seamlessly, colored PV panels in general offer the potential to match and even enhance a building's appearance, especially when thoughtfully chosen to harmonize with façade materials. This duality, between camouflage and visual expression, suggests that future solar installations should balance functional performance with contextual aesthetics to foster public acceptance and appreciation. Advances in color PV technologies, such as MorphoColor®, may provide an effective means of achieving broader public acceptance and more architecturally integrated solar solutions.

ACKNOWLEDGMENT

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